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TAMPERE UNIVERSITY OF TECHNOLOGY

MARIA KOUDINOVA
IMPROVING ON-TIME DELIVERY IN A MULTI-PRODUCT ASSEMBLY FACTORY

Master of Science Thesis

Examiner: Professor Jussi Heikkilä
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ABSTRACT

MARIA KOUDINOVA: Improving on-time delivery in a multi-product assembly factory
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The objective of the study was to improve production planning and control (PPC) practices to answer current and, especially, future needs at Wärtsilä Suzhou Ltd. (WSZ) in China producing various product lines for the marine market. The main research question was: *"How to organise PPC at WSZ so that it is responsive to the needs of a multi-product factory?"* The study was conducted as an applied case study. The research methods used were unstructured interviews, benchmarking to other delivery centres, interventions and observation. Data for analysis was taken from the company's ERP-system and manually recorded spreadsheets. The main finding was an under 20% on-time delivery (OTD) performance caused by a lack of systematic PPC practices, with employees not knowing the status of orders they are responsible for. Additionally, material shortages in production lead to high levels of work in process (WIP) and long lead times.

From PPC frameworks aggregate planning combines demand to the level of resources over a fixed planning horizon, quick response manufacturing emphasises lead time reduction and workload control levels workload to capacity. None of the above are fully applicable to the context of WSZ, so solution searching was done through benchmarking and interventions. Interventions carried out were full-kitting to improve work flow and material availability management to proactively monitor material arrival. For full-kitted products on-time start of assembly (SoA) was not possible if there was no floor or worker capacity. Also, new ways of working were not sustained showing a gap between strategic decisions and actions. This was explained by the cultural context of China, where supervision is expected.

The output of this thesis is an outline of PPC practices to improve WSZ's OTD performance through taking responsibility, being disciplined and forward-looking. Slot planning could be used for production planning to base scheduling on floor and worker capacity. Weekly meetings should be held to discuss production enabler availability for products with planned SoA during the next eight weeks. Using a "traffic lights" tool would help in-house tracking and communicating the accurate status of orders to the internal customer. Full-kitting should be continued as implemented, but material availability management should be improved to require less buyer resources.

TIIVISTELMÄ

MARIA KOUDINOVA: Toimitusvarmuuden parantaminen monituotekokoonpanotehtaassa
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Avainsanat: tuotannon suunnittelu ja ohjaus, valmistus tilauksen mukaan, materiaalin kokonaiskeräys, standardimuotoisesti aikataulutettu suunnittelu

Työn tavoitteena oli parantaa tuotannon suunnittelun ja ohjauksen menetelmiä vastaamaan meriteollisuuteen useita tuoteperheitä valmistavan Wärtsilä Suzhou Ltd:n (WSZ) nykyisiä ja tulevia tarpeita. Tutkimuskysymys oli: *”Miten järjestää WSZ:n tuotannon suunnittelu ja ohjaus niin, että se vastaa monituotetehtaan tarpeisiin?”* Työ toteutettiin tapaustutkimuksena. Tutkimusmenetelminä käytettiin avoimia haastatteluja, vertailuoppimista muihin toimitusyksiköihin, interventioita ja havainnointia. Aineisto otettiin yrityksen ERP-järjestelmästä ja käsin ylläpidetyistä Excel-taulukoista. Työn päähavainto oli alle 20%:n toimitusvarmuuteen johtanut epäjärjestelmällinen tuotannon suunnittelu ja ohjaus, missä vastuuhenkilöt eivät tiedä tilaustensa tilannetta. Lisäksi materiaalipuutteet tuotannossa aiheuttivat suuren keskeneräisen tuotannon määrän ja pitkät läpimenoajat.

Teoriamalleista kokonaissuunnittelussa (*aggregate planning*) kysyntä tasapainotetaan suunnitteluajanjakson resurssitasoon, nopean vastausajan valmistamisessa (*quick response manufacturing*) lyhennetään läpimenoaikoja ja työkuormituksen kontrollissa (*workload control*) työmäärä tasapainotetaan kapasiteettiin. Nämä evät täysin sovi WSZ:n ympäristöön, joten ratkaisua haettiin vertailuoppimisella ja interventioilla. Interventioina toteutettiin tuotannon aloitusta edeltävä materiaalin kokonaiskeräys (*full-kit*) työvirtauksen sujuvoittamiseksi ja materiaalin saapumista seurattiin ennakoivalla materiaalisaatavuuden hallinnalla. Kokonaiskerättyjen tuotteiden valmistus aikataulun mukaan tapahtui vain lattia- ja työntekijäkapasiteetin riittäessä. Lisäksi uusia menetelmiä ei ylläpidetty osoittaen eron strategisten päätösten ja toimintatapojen välillä. Tätä selitettiin Kiinan kulttuurikontekstilla, missä odotetaan jatkuvaa ylemmän tason valvontaa.

Työn tuloksena on WSZ:n toimitusvarmuuden paranemiseen johtava vastuun kantamiseen, itsekuriin ja ennakointiin perustuva tuotannon suunnittelu ja ohjaus. Standardimuotoisesti aikataulutettua suunnittelua (*slot planning*) ehdotetaan käytettävän lattia- ja työntekijäkapasiteetin sisällyttämiseksi tuotannon suunnitteluun. Viikoittain tulisi tarkistaa seuraavan kahdeksan viikon aikana tuotannon aloittavien tilausten materiaalisaatavuus. ”Liikennevalotyökalun” käyttö auttaisi tilausten tilanteen seuraamista ja tarkan tiedon jakamista sisäiselle asiakkaalle. Interventioista ensimmäistä tulisi jatkaa, mutta jälkimmäistä tulisi parantaa, jotta se sitoisi vähemmän ostotiimin resursseja.

FOREWORD

This thesis was written at Wärtsilä Suzhou Ltd. in China and would not have been possible without the warm welcome, support and collaboration of the people here. A special thank you goes to my "mother", Julia Shi, who organised the most thorough training I could hope for and kept answering all the detailed questions I came to her with. A huge thank you to my boss, Jussi Heikkola, who read manuscript after manuscript, asked all the right and tough questions, coached, guided and believed in me. Your attention to detail while seeing the bigger picture is something I am still learning.

A thank you goes to the people interviewed at the delivery centres in Vaasa, Finland and Trieste, Italy, for sharing details on how things work elsewhere. Toni Lagerström and Jyrki Ylipulli, I am grateful for all the insightful discussions we had.

The love and support from my family has brought me this far: my mother who told me I could be anything, my father who thinks I am stubborn beyond measure and my grandparents who always wonder how I manage to study while constantly traveling. To a dear friend who joked that I will never graduate, I am sorry you are not here to see it. To all the close friends, thank you for being there, listening and reminding me to make the decision that I feel is right.

Applying to study at Tampere University of Technology was one of the best decisions of my life and I am glad I got to graduate from a university that gave me so much, especially in the form of extra-curricular activities and opportunities to go on exchange. Without the latter I doubt I would have ended up writing my thesis in China. Thank you Professor Jussi Heikkilä for sharing all the literature to properly start on this thesis and being so accommodating to my last-minute schedule changes.

In Suzhou, China, 9th of November 2018

Maria Kudinova

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ABBREVIATIONS AND NOTATIONS

CCR	capacity constraint resources
COBACABANA	control of balance by card-based navigation
DCT	Delivery Centre Trieste, Wärtsilä's factory located in Trieste, Italy
DCV	Delivery Centre Vaasa, Wärtsilä's factory located in Vaasa, Finland
EBOM	engineering bill of materials
ECN	engineering change notice
ECR	engineering change request
ERP	enterprise resource planning
EXW	ex works, Incoterms
FAT	factory acceptance test
FOB	free on board, Incoterms
FTMS	focused target market segment
HPP	hierarchical production planning
KPI	key performance indicator
MBOM	manufacturing bill of materials, at WSZ called PBOM
MCT	manufacturing critical path time
MPS	master production schedule
MRP II	manufacturing resource planning
MRP	material requirements planning
MTO	make-to-order
OA	order acknowledgment
ODD	operation due date
OTD	on-time delivery
PBOM	production bill of materials
PLT	purchasing lead time
PO	purchase order
PPC	production planning and control
QC	quality control
QRM	quick response manufacturing
Q-ROC	quick response office cell
RTC	retrofit sewage treatment plant
SAP	ERP-system used at WSZ
SFTT	shop floor throughput time
SoA	start of assembly
SPT	shortest processing time
STC	sewage treatment plant
TOC	theory of constraints
WIP	work in process
WLC	workload control
WSZ	Wärtsilä Suzhou Ltd.

1. INTRODUCTION

1.1 Company background

Wärtsilä Suzhou Ltd. (WSZ) is a multi-product assembly factory located in Suzhou, China. Currently, it employs 130 white- and blue-collar workers. The factory, founded in 1998, became part of Wärtsilä, when the Wärtsilä corporation acquired Hamworthy in 2012 (Wärtsilä Hamworthy 2018). Wärtsilä is a global Finnish company providing advanced technologies and complete life-cycle solutions for the marine and energy markets, offering sales and service in over 200 locations in more than 80 countries. The company operates primarily through subsidiaries and strategic joint ventures. Manufacturing is assembly based with ca. 1120 key direct suppliers in Europe and Asia, which represents 93% of the company's total supplier spend. Thus, developing long-term relationships with its global network of suppliers is a key priority. (Wärtsilä annual report 2017)

In 2017 Wärtsilä had around 18 000 employees, its sales were 4923 million euros, of which 97,7% outside of Finland, and it made a profit of 383 million euros (Wärtsilä annual report 2017). The portion of net sales and number of employees by industry is shown in Figure 1. Out of Wärtsilä's three business lines, Marine Solutions, Energy Solutions and Services, the first is WSZ's main customer.

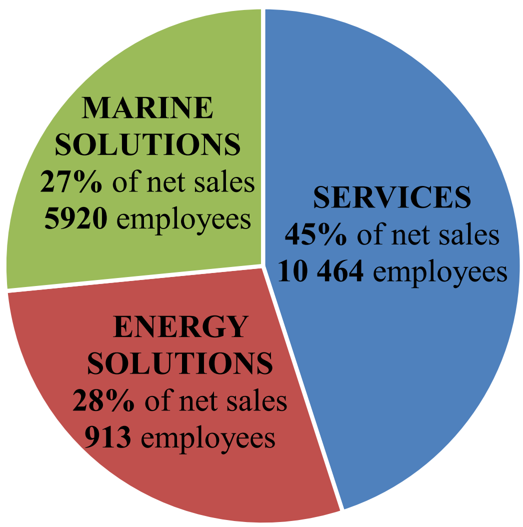


Figure 1. Portion of net sales and number of employees by industry. (Wärtsilä annual report 2017).

At WSZ production is based on assembling products from raw materials, parts and components. The production of the latter is outsourced, however final assembly is done in-house to ensure keeping up to quality standards. This, by definition, constitutes make-to-order (MTO) production (Jacobs et al. 2011, p.49). There are ten product lines, but products are tailored to customer specifications, making the product portfolio complex. At WSZ a product line is a grouping of related products with the same end-function. Production is mostly by manual labour and there is high worker flexibility in the sense that the same people can work on multiple product lines. Additional workforce for production can be rented, making it a constraint only in short term decision making.

The orders come mostly from Wärtsilä's internal customers called "product companies", other Wärtsilä units who take care of sales. The majority of orders come from offices located in Poole, the U.K., Moss, Norway and Svanehøj, Denmark. Thus, WSZ is an internal supplier for the Wärtsilä corporation. Currently order processing works so, that based on the request of the product company, the planner agrees on a date of delivery, that is the date WSZ is ready to ship the product. This is set according to the purchasing lead times (PLT). The date is entered into SAP, the enterprise resource planning (ERP) software used at the company since the 1st of January 2015, which calculates a set of other dates needed for the order processing, e.g. date of material purchasing and start of assembly (SoA).

For most product lines the purchasing of materials is done based on the manufacturing bill of materials (MBOM), called the PBOM (production bill of materials) at WSZ, created by engineers in-house. The PBOM is prepared by the engineers based on the engineering BOM (EBOM) which in turn is based on the purchase order (PO) both received from the product company. The incoming material is checked by the quality department before it is placed in the warehouse and released into production. Ready products are checked by the quality department and sometimes the contract with the customer requires to run a separate quality check called a factory acceptance test (FAT). The customer can request to be present for the FAT. If the product passes the FAT, WSZ asks the product company for shipping details, sends an invoice to the product company and packs the product for delivery to the customer. The basic order processing operation is shown in Figure 2.

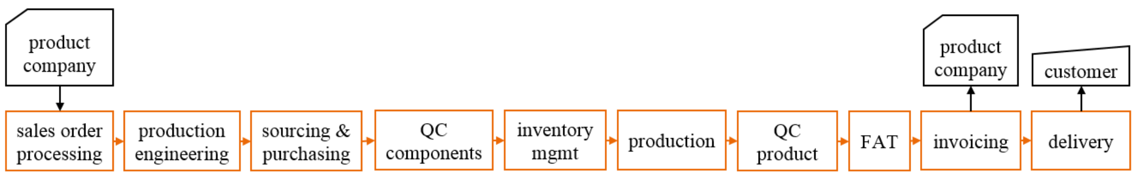


Figure 2. Basic order processing operation at WSZ.

If the product does not pass the FAT an engineering change notice (ECN) is issued internally and WSZ corrects the product. After this the customer may request another FAT, the product is invoiced from the product company and WSZ prepares the product for delivery. The packing and logistics are outsourced.

1.2 Research background

During the past five years the amount of product lines handled at WSZ has been increasing at an average rate of one new product line each year as the product portfolio of the Wärtsilä corporation has widened, production has been moved from Europe to China and the factories in China consolidated. The number of product lines at WSZ over time is shown in Figure 3. This has reflected on production dependability as processes like planning, purchasing and production have not had time to adjust to the increased complexity of the product portfolio.

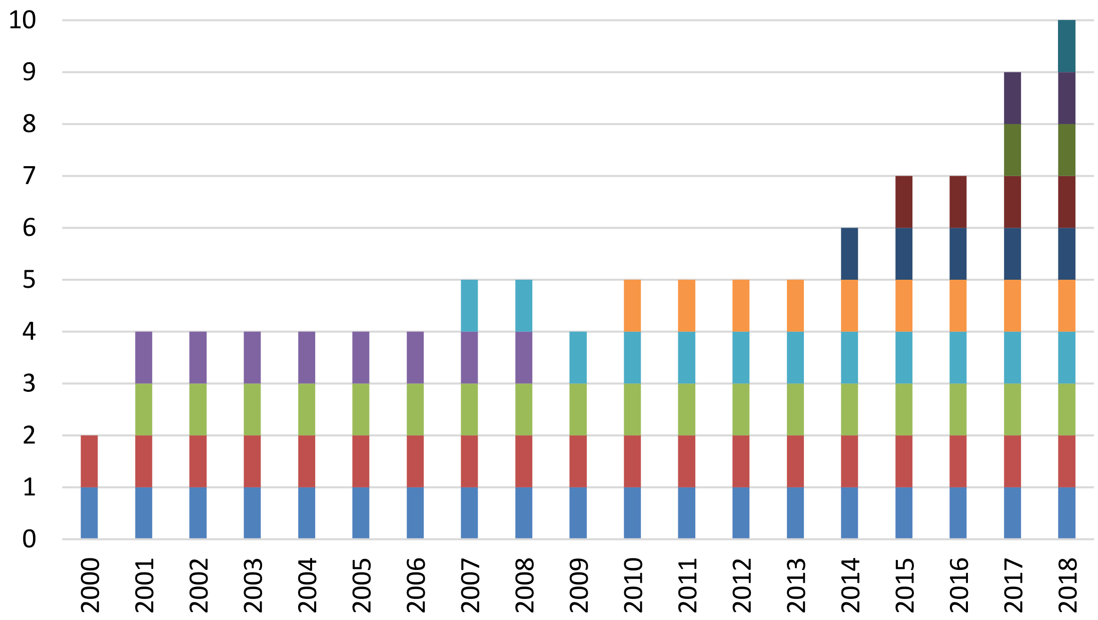


Figure 3. Number of product lines at WSZ over time, where each colour represents one product line.

At a glance issues are related to planning being incapable of prioritising orders and knowing their status, purchasing being unsure which supplier to chase from all the late suppliers and production having a lot of work in process (WIP) from orders whose production has been halted due to material shortages noticed in production. The way of working seems to rely on taking corrective actions and last-minute firefighting instead of planning ahead and taking preventive action. This all translates into long lead times and difficulties to deliver products on time. In order to stay competitive in the marine industry, it is vital for WSZ to be able to provide stable and predictable lead times and, thus, deliver products to its customers according to the promised delivery date. This may require changes in how the operation processes, especially planning and its communication to purchasing and production are currently carried out.

1.3 Research problem and objective

The goal of any for-profit organisation is to make money (Goldratt 2014). In the case of WSZ this means selling products to customers based on the given specifications. Since the products are usually part the customer's bigger project, it is important the products answer the customer's requirements and are delivered on time. This research aims to address some of the issues WSZ faces with on-time delivery (OTD). To identify the root cause for late deliveries at WSZ a current reality tree of the sewage treatment plant (STC) product line was constructed. The current reality tree is shown in Appendix 1. This product line was chosen for multiple reasons. Firstly, the product has been assembled at WSZ for nearly 20 years, so there is a lot of experience based in-house knowledge. The assembly process is not complex and can be standardised. Additionally, the volumes are high enough to provide an adequate amount of data.

Based on the current reality tree, it can be said, that the main reason for late deliveries is the lack of systematic production planning and control. Instead of preventive actions and forward-looking the mode of work centres around last-minute corrective measures. According to Goldratt (1994, p. 94) the problem with firefighting is that it creates an impression that you are surrounded by a vast amount of independent problems, when actually there is a link between them. By establishing the causes and effects the one or two core causes can be identified. The rest are undesirable effects. (Goldratt 1994, p. 95) This is also the logic behind identifying issues in production planning and control to be the core cause of the other problems present at WSZ.

The term *production planning* is used to refer to the collective set of actions related to integrating information on forecasts, orders, production capacity, on-hand inventory quantities, bills of material, work in process, schedules and production lead times (Stevenson 2015, p. 517). *Control* as defined by the Merriam-Webster dictionary (2018) refers to exercising "restraining or directing influence over", applied in this case, to the above-mentioned. *Production planning and control* (PPC) as a single term is also used to denote systems whose functions include planning material requirements, demand management, capacity planning and the scheduling and sequencing of jobs with the aim to reduce WIP, minimise shop floor throughput times (SFTT) and lead times, and improve OTD performance (Stevenson, Hendry & Kingsman 2005), thus combining the definitions for the terms above.

The objective of the study is to **improve production planning and control practices at WSZ, so they answer to current and, especially, future needs**. Both, defining the phrase *production planning and control* in two parts or as a managerial approach, are applied in this case, as suggestions for practices will also be taken from existing frameworks. The scope is *production* as a broader term encompassing inputs and outputs, as opposed to manufacturing which covers converting raw material into finished products.

The term *practices* indicates both “repeated or customary action” and “actual performance and application” (Merriam-Webster 2018), since the intention is to have a model of actions which are applicable to real life as opposed to working in theory. Future needs encompass a consideration for increasing volumes and variety of products coupled with stricter demands towards OTD performance from the customers.

Thus, the main question the thesis aims to answer is:

How to organise production planning and control at WSZ so that it is responsive to the needs of a multi-product factory?

To answer the main question, the following sub-questions should be answered:

- How is production planning and control currently organised?
- How should production planning and control ideally be organised at WSZ?
- What are the pre-requisites and information needed to achieve these ideal production planning and control practices?

1.4 Research methodology, scope and schedule

From a research methodological point of view the thesis is an applied case study with the purpose of improving a specific problem the case company faces by applying available theoretical frameworks and interventions to it. From the research philosophies described by Saunders et al. (2009) this research aims to be objective and realistic, though with an allowance to misinterpretation arising from working in an organisation where people have a very different cultural background and thus a differing communication and working style compared to the author’s. The research approach is deductive starting with analysing the present situation of the case company to derive a logical conclusion from the given premises. At the same time, it is an exploratory operations management research with the aim of solving a concrete practical problem (Holmström et al. 2009).

The research is a longitudal multi-method research, so both quantitative and qualitative data will be collected. Quantitative data will be mainly collected from SAP, the enterprise resource planning software used in the company. This will be supplemented by data related to issues during purchasing and production collected manually into spreadsheets by the respective units. Qualitative data will be gathered by observing the processes in the organisation, carrying out unstructured interviews and collecting written and oral feedback when implementing changes.

The research will start as a case study where the initial qualitative data collected will be analysed using Eliyahu Goldratt’s logical thinking process, shown in Figure 4. Quantitative data will be used to support the points raised by the thinking process. Theoretical frameworks gathered from literature and benchmarking to other Wärtsilä units will be applied to the problem at hand, thus adding an interventionist dimension to the research.

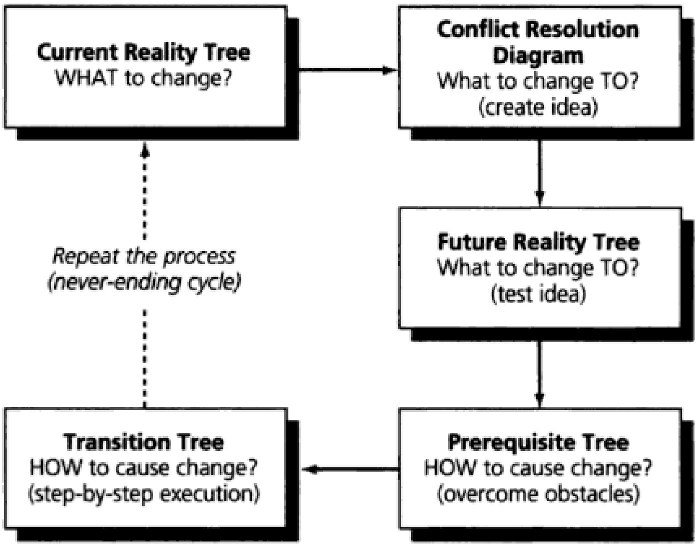


Figure 4. The five logical tools as an integrated thinking process. (Dettmer 1998, p. 28)

Based on the issues raised in the sewage treatment system's production planning and control current reality tree the following quantitative data will be collected:

- What is the rate of production, that is how many products are invoiced monthly?
- What is the production lead time from the point when the product is released into production to when production is finished?
- What is the percentage of products that are delivered by the customer requested EXW date?
- What is the ratio of ECNs raised before to after the freezing point?

This data will then be compared to the same values collected during the interventions.

The output will be a proposal of production planning and control practices first to be implemented and tested on the STC product line, after which they should be adjusted and implemented to other product lines, especially ballast water management systems (BWMS). This scope is chosen, because the STC product line has upcoming orders and the process from the point when the order is received to the dispatch of the ready product can be standardised. STC and BWMS come from the same product company, which is proactive in carrying out improvements. This makes it realistic to involve the product company in the process once the practices start to be implemented. The actual research schedule is shown in Figure 5.

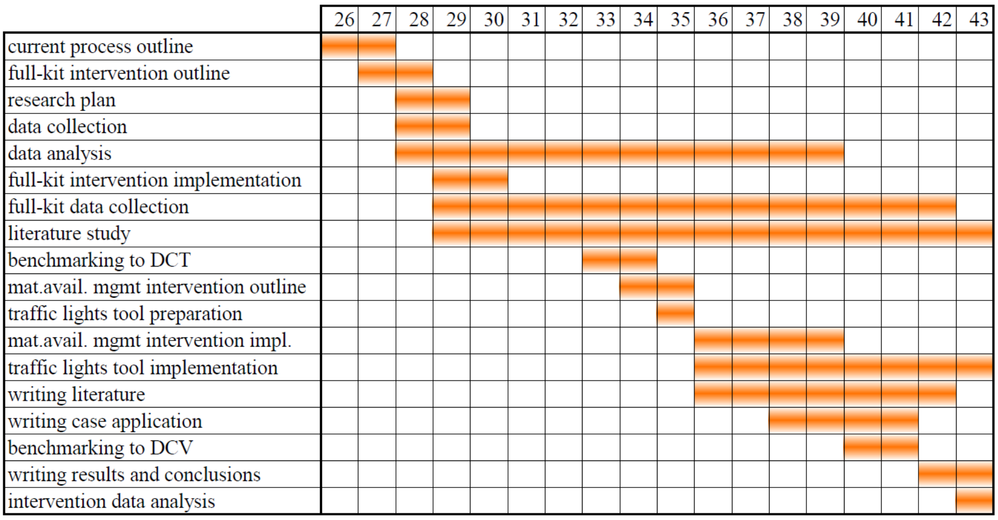


Figure 5. Research schedule.

The actual schedule is shown instead of a planned one, because at the start of the research all the steps were not clear. The study started with getting acquainted with the current processes at WSZ. Two interventions were carried out and data collected on them. A “traffic lights” tool was implemented as an extension to the traffic lights tool used in other product lines. Benchmarking was done against the delivery centre in Trieste, Italy (DCT) and the delivery centre in Vaasa, Finland (DCV). Throughout the research literature was studied to broaden the understanding of production planning and control.

1.5 Structure of the thesis

The thesis is divided into four chapters. In chapter 1 the background of the company and the research are given. In Chapter 2 the theoretical frameworks applicable to the research problem are described and discussed.

Chapter 3 is divided into three parts. First the current state is given through qualitative and quantitative analysis. Next the desired future state is described. The third part gives a concrete outline of the practices that should be implemented along with a description of the two interventions carried out.

Chapter 4 states the learnings from the interventions, offers a discussion on the achievement of the objective of this thesis and gives recommendations on how WSZ should continue onwards. At the end there is an appendix with additional details that support understanding the core of the thesis.

2. LITERATURE STUDY

2.1 From aggregate planning to constraint scheduling

2.1.1 Goal of aggregate planning

Aggregate production planning is an intermediate-range capacity planning (Stevenson 2015, p. 457), as opposed to short-range more operational planning and long-range strategic planning. The different planning levels are shown in Figure 6. The concept of aggregate planning was developed by Charles Holt, Franco Modigliani, John Muth and Herbert Simon in the early 1950s while they were working on a project studying planning and control of industrial operations (Singhal & Singhal 2007). Aggregate production planning can be used to cover a horizon of 2 to 12 months. Some organisations use the term "sales and operations planning" for this type of planning. (Stevenson 2015, p. 457) However, according to Jacobs et al. (2011, p. 116) sales and operations planning is more top-level providing a link between strategic, financial and marketing planning. There are also authors who use the terms aggregate planning and sales and operations planning interchangeably, and those who see aggregate production planning as a part of the sales and operations planning process (Olhager et al. 2001, p. 219).

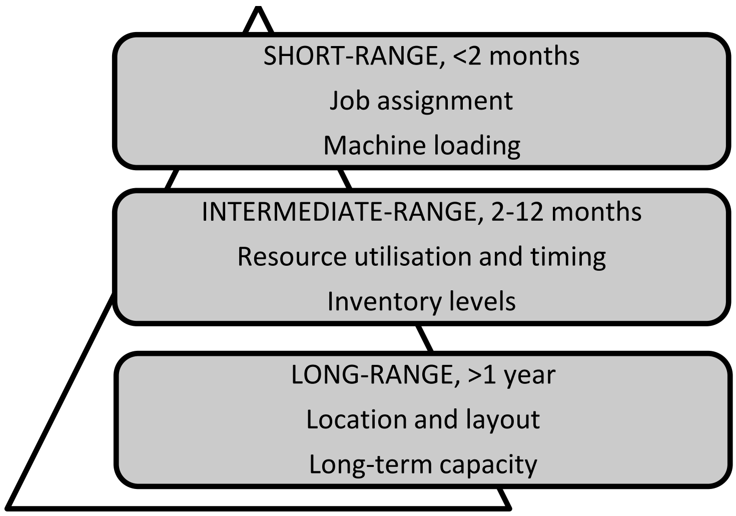


Figure 6. Levels of planning.

According to Stevenson (2015, p. 457) in sales and operations planning intermediate-range decisions balancing supply and demand are made by integrating financial and operations planning, so the inputs come from sales as a demand forecast, from finance as financial constraints and from operations as capacity constraints. The inputs for aggregate planning is information on available resources, both workforce and facilities, the demand forecast, policies and workforce change, subcontracting, overtime, inventory levels or changes in inventory, back orders and costs related to the above (Stevenson 2015, p. 461). In this thesis we will use Stevenson's understanding of aggregate planning, which emphasises manufacturing related inputs.

The goal of aggregate planning is to utilise effectively the organisation's resources to match expected demand. This type of planning is useful for organisations that experience fluctuating demand or capacity. (Stevenson 2015, p. 457) Additionally aggregate planning serves as a means for implementing both manufacturing and supply chain strategy. Concerning the first, it deals with trade-offs between cost, flexibility and delivery time. Concerning the second, it alleviates the impact of the bullwhip effect by defining the product mix, material requirements, levels of procurement, the flow of material downstream in the supply chain and the timing of order fulfilment. (Singhal & Singhal 2007) The bullwhip effect refers to the increasing oscillations in inventory demand when looking backward in the supply chain (Stevenson 2015, p. 670). With aggregate planning demand level is stable throughout the supply chain.

In order to make decisions, planners aggregate i.e. group the products into categories (Stevenson 2015, p. 457). At WSZ products are aggregated into product lines based on their function, even though each product inside a product line is engineered to answer the customer's needs. The purpose of aggregating the products is to simplify calculations by expressing the needed information on sales forecasts, inventory levels, labour inputs and production rates in a reasonable format (Buxey 2003).

2.1.2 Strategic decisions in aggregate planning

In the make-to-order environment uncertainty is for the most part related to the level of company resources needed to complete the engineering and produce the product once the order specific requirements are available. For demand management this means coordinating information on customers' product needs with engineering and then transforming this into components that need to be purchased to start manufacturing. (Jacobs et al. 2011, pp. 52-55) In order to meet uneven demand planners can adopt a number of strategies, like maintaining a level workforce, meaning the number of workers does not change, maintaining a steady output rate or matching demand period by period (Pan & Kleiner 1995). These can be divided into two pure production strategies companies can follow: a level strategy or a chase strategy. In the first case, a steady production rate is maintained over the year. In the second case the expected monthly sales are tracked and then the corresponding labour requirements calculated. This translates into altering one of or both demand and capacity. Alternatively, a mix of the two strategies can be used. (Buxey 2003)

The choice of demand management strategy depends on the environment. Environments are classified based on the order penetration point (OPP), also called the customer order decoupling point. OPP is the point where the company, as opposed to the customer, becomes responsible for scheduling and managing the material quantity to be purchased, produced or finished. (Jacobs et al. 2011, p. 48) In the make-to-stock environment, where the OPP is close to the customer, a level strategy is feasible to use. At the other end of the spectrum is the engineer-to-order environment, where only a chase strategy is possible, since demand dependent information is available only for the near future (Jacobs et al. 2011, p. 51). OPPs for different environments are shown in Figure 7. The blue colour indicates demand independent operations and the green colour shows demand dependent operations. The latter is what customers experience as lead time.

	INVENTORY LOCATION			
	suppliers	raw materials	WIP parts and components	finished goods
make-to-stock (MTS)				OPP
assemble-to-order (ATO)			OPP	
make-to-order (MTO)		OPP		
engineer-to-order (ETO)	OPP			

Figure 7. Customer OPPs in different environments.

Demand can be altered through pricing, promotion, back orders and new demand. Capacity, that is the resource supply of the company, can be altered through hiring and laying off workers, overtime and slack time, hiring part-time workers, carrying inventory and subcontracting. In practice companies will combine different options. (Stevenson 2015, pp. 461–465) The industry trend is to follow the chase strategy, which has been stimulated by the spread of just-in-time production. It is also a realistic option when production tasks are easy to learn. (Buxey 2003)

All the options include costs and imply decisions to be made regarding trade-offs. The effect of back orders and lost demand on customer service level, inventory levels, the stability of the workforce and costs need to be considered. If demand is taken as a given the costs to consider are hiring and layoff costs, overtime and undertime costs, inventory carrying costs, part-time labour costs, stockout costs and back order costs. (Pan & Kleiner 1995)

2.1.3 Aggregate plan to constraint-based production schedule

In the long-range capital expenditures are matched against projected market requirements. This is done to determine a plant's maximum capacity limits and the estimated utilisation to determine whether its functioning is economically viable. In the medium-range the aggregate plan is used to establish the total monthly production rates, the monthly workforce needed for this and the finished goods inventory levels. To generate a master production schedule (MPS), the aggregate production totals are disaggregated back into specific product requirements of separate orders. (Buxey 2003) The MPS, or master schedule, shows the quantity and timing of concrete end items for a scheduled horizon. This usually covers six to eight weeks. (Stevenson 2015, p. 477) In make-to-order companies one MPS unit is usually one end item or set of items composing a customer order (Jacobs et al. 2011, p. 186).

To minimise scheduling problems managers can:

- Set realistic due dates.
- Focus on bottleneck operations.
- Consider lot splitting for large jobs. (Stevenson 2015, p. 710)

When setting due dates, it is worth remembering, that customers prefer honest answers, even if they are unpleasant, to inaccurate information (Jacobs et al. 2011, p. 62). In the make-to-order environment the main activity is controlling the progress of customer orders to meet the promised delivery dates. Any changes in e.g. engineering or manufacturing need to be communicated to the master production scheduler so he can determine their impact on the final delivery to the customer. (Jacobs et al. 2011, p. 56)

Focusing on bottlenecks can be understood as knowing where they are and what effect they have on the overall process. Regarding focusing on bottlenecks there is an approach called the Theory of constraints (TOC) popularised by Eliyahu Goldratt (Jacobs et al. 2011, p. 298). The theory builds on managing constraint i.e. bottleneck usage, because an hour lost at a bottleneck operation is an hour lost for the whole system and thus determines the overall capacity of the system. Production should be planned so, that the bottleneck's time is not wasted by e.g. sitting idle, processing defective parts or working on parts not needed. (Goldratt 2014, pp. 164-165) The difference between a bottleneck and non-bottleneck is that improving the former will lead to higher output, whereas changes in the latter will not increase the ultimate output of the system. (Goldratt 2014, p. 145)

Goldratt (2014, p. 313) describes a five-step process to manage bottlenecks:

1. *Identify* the system's constraint(s).
2. Decide how to *exploit* the system's constraint(s).
3. *Subordinate* everything else to the above decision.
4. *Elevate* the system's constraint(s).
5. If in the previous steps a constraint has been broken, go back to step 1, but do not allow *inertia* to cause a system's constraint.

The TOC approach starts by determining the bottleneck work centres and continues by trying to find solutions how to develop the bottleneck. Scheduling concentrates on the best way to manage bottleneck capacity. (Jacobs et al. 2011, p. 299) Finite forward scheduling is used for bottleneck work centres (Jacobs et al. 2011, p. 329). Finite refers to considering planned capacity utilisation when scheduling (Jacobs et al. 2011, p. 278). Step 5 is especially important, because it indicates the possibility that improving the performance of a bottleneck may shift the bottleneck elsewhere. It also broaches the existence of capacity constraint resources (CCR), which are not bottlenecks by themselves, but the sequence in which they perform their jobs can create a constraint (Goldratt 2014, p. 284). If there is no need to increase capacity carrying out the three first steps is enough.

To better manage bottlenecks TOC uses buffers through both safety stock and safety lead time. The reasoning behind adding a safety stock before a bottleneck operation is to provide a cushion against variation, which affects negatively job flow. (Jacobs et al. 2011, p. 330) When calculating the safety lead time i.e. time buffer a good rule of thumb is to consider the current production lead time and cut it in half. This is then added to the overall production lead time. (Goldratt 1997, p. 149)

The third way to minimise scheduling problems is lot splitting (Stevenson 2015, p.710). Lot splitting means starting to produce an order at a next work centre before it is completed at a previous work centre. This type of flexibility makes better use of capacity, which is especially important at the bottleneck resource. When an order is completed based on custom priority scheduling rules, the highest priority order in the queue is selected for processing. Because a work centre can contain transfer batches coming from many released orders, the queue is searched for other orders containing the same requirements for work centre set-up as the order chosen by priority scheduling rules. This saves set-up time at the bottleneck work centre. (Jacobs et al. 2011, p. 333)

Buxey (2003) mentions that hierarchical production planning (HPP) has been successful in integrating MPS and aggregate plan development with the help of different linear programming models. The hierarchical model divides the problem into a series of subproblems, which helps reduce its complexity. HPP matches product aggregations to decision-making levels in the organisation and consists of four models: forecasting, aggregate production planning, disaggregate production planning and sequencing. (Pan & Kleiner 1995)

2.2 Quick response manufacturing

2.2.1 Goal of quick response manufacturing

Competitiveness, meaning how effectively an organisation meets the wants and needs of customers when comparing to others who offer similar goods or services, is the cornerstone when determining whether a company prospers or not. Competitiveness can be achieved through improving interrelated operations, including response time. (Stevenson 2015, p. 42) Quick response manufacturing (QRM) is a company-wide strategy that focuses on reducing lead time (Emboava, Cardoso & Tammela 2017). From the customer perspective, lead time is the time between submitting an order and receiving it (Stevenson 2015, p. 553). Lead time is critical and offering products with short lead times can be a major competitive advantage (Suri 2015).

Shop floor throughput time is a part of overall order lead time. It is the time between the arrival of raw materials to the factory and the shipment of the finished product. Reducing throughput time is the single most important element of improved factory productivity. When managers focus on throughput time, they are forced to reduce inventories, setup time and lot sizes. (Schmenner 1988) The relationship between lead times and inventory levels is quantified by Little's law:

$$L = \lambda W$$

It is a purely mathematical tautology according to which the average amount of items in a queuing system i.e. inventory (L) is equal to the average rate at which items enter that system (λ) multiplied by the average time an item spends in the system (W). (Little & Graves 2008) As an example, if a unit is in the system on average 7 days and the demand or the average rate at which items enter the system is 2 units a day, the average inventory is 14 units. If the lead time were shorter the average inventory would decrease.

Worth noting is that making things fast is not the same as operating the fastest machines or having the most automation. It is about designing and organising a factory in which materials are in a constant forward flow. This requires quick setups, a compact and rational layout and low levels of WIP. (Schmenner 1988) Since the goal of a company is to make money, which can be achieved by increasing throughput while simultaneously reducing both inventory and operation expenses (Goldratt 2014, p. 73), focusing on throughput time is in line with the goal.

QRM is designed for companies offering a variety of products which can also be custom-engineered. Companies face different variabilities: dysfunctional variability caused by errors and poor systems and strategic variability implemented by a company to gain competitive advantage. (Suri 2010a) QRM aims to eliminate the dysfunctional variability which is caused by errors and deviations in the processes (Emboava, Cardoso & Tammela 2017), but exploits the second, which means that QRM also works in environments, where lean might not. As a result, the company should be able to deliver customised products rapidly while simultaneously reducing internal lead times, improving quality and lowering costs. Lead time and cost reductions make it possible to compete against low-wage countries. (Suri 2010a)

2.2.2 Lead time in quick response manufacturing

Understanding QRM starts by defining "lead time". Traditionally lead time is defined from the point the order is placed to the point the order is received. This does not give a clear picture of how order fulfilment is done, neither does it capture the waste in the process. Manufacturing critical path time (MCT) is a time-based metric to define lead time in a way that quantifies the longest critical path duration of order fulfilment activities helping to identify systemwide waste. (Suri 2015)

Suri (2010b, p. 39) talks about response time spirals to describe the dysfunctionality effects caused by wrong thinking. In the MTO environment, where forecasts cannot be used to build products in advance, there is a heavy reliability on the master schedule when managing purchasing and production (Suri 2010b, p. 39). The response spiral for the make-to-order products is shown in Figure 8. It starts from the assumption, that invariably there will be long lead times. Long lead times can be caused by long purchasing times or slow office operations, for which a separate response time spiral can be constructed. The longer the lead time the more inaccuracy there is and the higher the probability for issues to arise. This is why planners insert "safety times" or buffers throughout the schedule, further lengthening the lead time. (Suri 2010b, pp. 40-107)

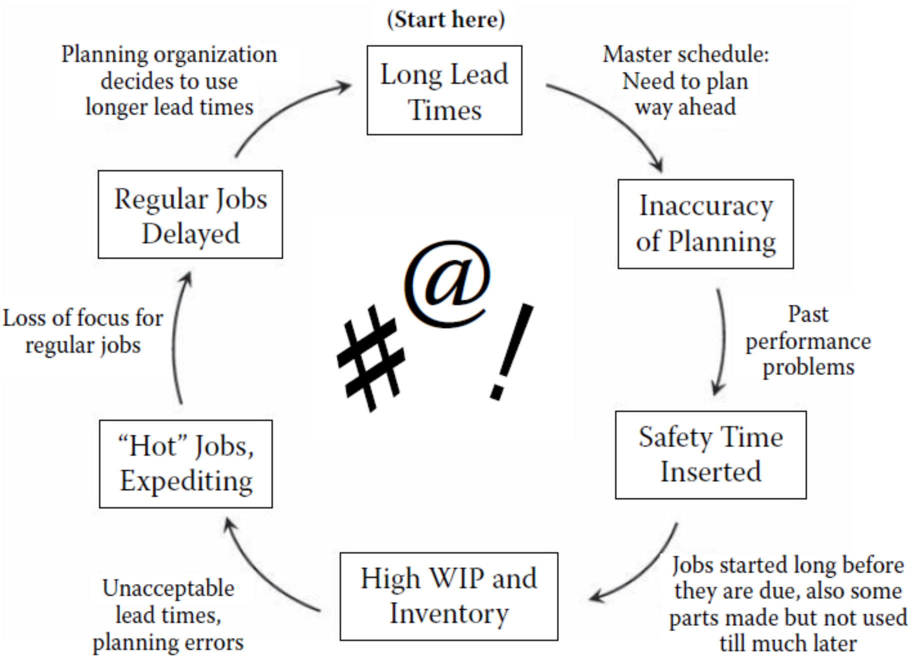


Figure 8. The response time spiral for make-to-order products (Suri 2010b, p.40).

Suri (2010b, p.40) gives an example from the engineering department, where a job that needs about 8 hours of an engineer's time is allowed two weeks to be finished. The planner rationalises this tenfold increase by the fact that the engineering department has multiple jobs to work on, so it may not be able to start on the particular job right away. Therefore, an additional five workdays are given. Based on experience the planner then notices that sometimes the engineering department gets urgent tasks, like warranty issues, production questions or time-sensitive sales inquiries, so another five workdays are added, changing a 1-workday job into a 10-workday job. To match the promised delivery dates these jobs with long lead times need to be started earlier than it would be otherwise necessary, thus increasing both WIP and inventory. (Suri 2010b, pp. 40-41)

Next a customer finds the long lead time unacceptable, so salespeople, to close the deal, promise a shorter lead time as an exception. This turns the order into a "hot" job which requires expediting to meet the due date, disrupting the progression of regular jobs. At some point these exceptions become the norm, because otherwise salespeople are unable to close deals. Production becomes even messier and the planning department starts adding even more buffer to the already long lead times, because they feel it is the only way to make on-time delivery possible. The long lead times start a new cycle or spiral of a dysfunctional process. (Suri 2010b, p.41) The spiral clearly shows the different waste caused by long lead times: overtime costs for trying to speed up late jobs, WIP and finished goods holding costs and space, late detection of quality problems. (Suri 2010a)

2.2.3 Production planning and control under QRM

QRM covers the whole organisation. It is not just about organising production to have shorter lead times, but generally incite a time-based mindset throughout the organisation; from the shop floor to office operations, materials planning systems, supply chain and finance. (Suri 2010b, p.105) Office operations include tasks like quoting, engineering, scheduling and order processing. These tend to be neglected as a source of improvement in manufacturing companies, yet they can consume over half of the quoted lead time. To visualise this a similar response time spiral as in *Figure 8* can be constructed for office operations. The only difference is that instead of high WIP and inventory, office operations suffer from a large number of active projects (Suri 2010b, pp. 106-107), which has lead Goldratt (1997, p. 126) to call multitasking “the biggest killer of lead time”.

To improve office operations first the focused target market segment (FTMS) has to be identified. Here “market” refers to an external or internal customer who requires the shorter response time. Then the office-processing steps for this segment are examined to find their “product”. The product can be a purchase order to a supplier or a work order released to the shop floor. Then a subset of the product is identified so simpler processing steps can be applied to it. The subset has to represent a significant enough demand for it to be worth focusing on, because a Quick Response Office Cell (Q-ROC) will be designed around it. A Q-ROC is a QRM cell for the office. (Suri 2010b, pp.112-113) A QRM cell completes an uninterrupted set of operations both on the shop floor and in the office for all jobs belonging to a specified FTMS (Suri 2010b, p. 50). The need to restructure the organisation to implement QRM will be discussed in chapter 2.2.4.

If the company’s usual measures are based on efficiency or utilisation goals, they need to start measuring MCT reduction through the QRM number for each Q-ROC (Suri 2010b, p.112). The QRM number is calculated with the following equation (Suri 2010b, p. 61):

$$\text{Current QRM number} = \frac{\text{base period MCT}}{\text{current period MCT}} \times 100$$

The way the current QRM number is calculated recognises better the effort put into changing the MCT than just comparing the current MCT to its previous value. An MCT of 27 days can be easily changed to 25 days just by removing buffers, whereas cutting a

MCT of 10 days to 8 days requires more effort. The QRM number also provides an equal starting point for comparing teams across the organisation, since everyone starts with the same base number of 100 even when the MCT and the operations the team performs differ. (Suri 2010b, pp. 60-63)

QRM requests to restructure the company's material-planning system. Even though material requirements planning (MRP), manufacturing resource planning (MRP II) and ERP have many enterprise-supporting functions, they do not aid MCT reduction. In some cases, their effect is the opposite creating another response time spiral, e.g. when an MRP system schedules a start date based on the lead times the planning departments inputs. Because these lead times are specified by planners ahead of time without knowing the actual workload of the other departments buffers are added making the lead time longer than it need be. The solutions offered by QRM is again to restructure the organisation into QRM cells and then align the company's MRP structure with its QRM strategy. MRP is then used for higher level planning of material flow from suppliers and between cells complementing this with POLCA, the QRM material control method for coordinating flows between cells. (Suri 2010b, pp. 123-125)

POLCA is the production control side of QRM. POLCA stands for paired-cell overlapping loops of card with authorisation. Unlike kanban, POLCA is designed to operate in environments with high variability or custom products. The pre-requisite is that production is divided into QRM cells. If material flows between two cells they form a loop. A pre-defined number of POLCA cards is assigned to travel the loop from the origin cell to the destination cell. When a POLCA card returns to the cell it left from it sends a message that there is available capacity in the downstream cell triggering a signal when a job is completed. (Suri 2010b, pp. 132-134) Since there are multiple cells in the system the loops overlap, which is shown in Figure 9.

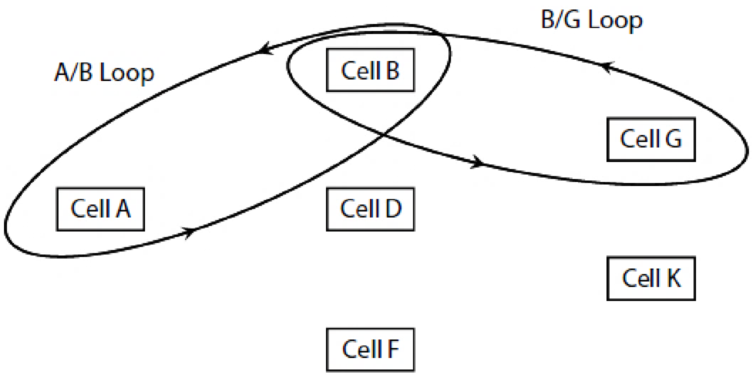


Figure 9. Overlapping loops between cells in POLCA. (Suri 2010b, p. 138)

Each cell has a dispatch list telling what date a job is authorised to start and the next cell it will travel to. Three conditions need to be met to start a job. First, the job or material needs to have arrived at the cell. Second, the authorisation date needs to be today or earlier. Third, the right POLCA card needs to be available. Sometimes this may result in production at a certain cell being at a standstill, which may seem like a waste. However, the truth is that starting production on jobs that have authorisation dates in the future will only steal capacity from another job that might be about to arrive, will create more WIP and ultimately add to MCT. (Suri 2010b, pp. 134-139)

2.2.4 Implementing quick response manufacturing

The main pre-requisite for QRM to work is changing organisational structure. There are four modifications that need to be carried out:

1- From functional to cellular, meaning an organisation of functional departments is transformed to consist of QRM cells.
2- From top-down control to team ownership, meaning that instead of managers or supervisors controlling departments the QRM teams govern themselves and their processes.
3- From narrowly focused workers to a cross-trained force, meaning that the instead of people specialising in performing a restricted set of tasks efficiently, they are trained to execute multiple tasks.
4- From efficiency or utilisation goals to lead time reduction, meaning a change from a cost-based to a time-based mindset. (Suri 2010a)

The last point can be linked to the idea promoted by TOC of moving from the cost world to the throughput world, where material flowing through the system is emphasised (Goldratt 2014, p. 304). Like TOC, QRM talks of the need to look at utilisation as more than the proportion of time a machine is running i.e. making parts. In QRM utilisation is “the ratio of the total time that the machine is occupied for any task, including the time it is unavailable due to maintenance, to the total time the factory is scheduled to work”. This definition of utilisation can be extended when viewing a person as a resource. (Suri 2010b, pp.77-78) The other important concept to understand is “flow time”. For a job arriving at a resource Suri (2010b, p. 78) defines it as ”the average time that it takes for a resource to finish other work that may be ahead of this job, start working on this job and finally complete it”, thus adding the time the job waits into its flow time. This leads to decreasing wait time, when taking action to decrease flow time, which in turn decreases MCT (Suri 2010b, pp. 78-79).

Suri (2010b, pp. 170-173) gives a four-step process on how to implement QRM into an organisation starting from creating awareness of the effect of time on the organisation’s operations to changing the organisational structure and unifying the time-based strategy throughout the organisation. The crux is to understand and exploit the system, which may require re-examining utilisation and batch sizing strategies. Emphasis should be placed on mindset over technology, because QRM challenges many traditional management beliefs, which need to be overcome for successful implementation (Suri 2010b, pp. 168-173).

2.3 Workload control

2.3.1 Goal of workload control

Workload control (WLC) is a production planning and control concept that is designed for the need of MTO companies, in particular for those with highly variable production systems (Thürer et al. 2014). According to Hopp & Spearman (2004) the variability of a production system is absorbed by three buffers: an inventory buffer, a capacity buffer and a lead time buffer. Safety stocks are an example of inventory buffer, additional floor space is an example of capacity buffer and planning with a longer production lead time is a form of lead time buffer. Lean production aims to protect throughput from variability by minimising buffers (Hopp & Spearman 2004). However, with the highly variable planning environment MTO companies face, it is often not possible to reduce this variability (Thürer et al. 2014).

Workload control, like the theory of constraints, emphasises a better use of buffers to handle variability (Thürer et al. 2017). This translates into being more effective with inventory, capacity and lead time buffers. The goal of WLC is to support the previous through integrating production and sales into a hierarchical system of workloads. WLC also integrates customer enquiry management, including a due-date setting rule with order release control. (Thürer et al. 2014)

2.3.2 Production planning and control under workload control

In WLC the planned and total workloads are controlled through customer enquiry management (CEM). The planned workload refers to all the confirmed orders, which includes the orders both on the shop floor and in the pre-shop pool. The total workload consists of not only the confirmed orders, but also an estimated future workload. There are two control levels, CEM and order release, which complement each other to reduce variability. CEM controls the lead time buffer and affects the capacity buffer through controlling the incoming workload to be in line with the available capacity. Order release balances the shop floor workload to reduce the required inventory buffer, so that capacity is used effectively. (Thürer et al. 2014)

CEM aims to overcome the conflict between production and sales functions, e.g. sales promising too close due dates, which are not realistic to reach from the perspective of production. There are three interdependent parts of CEM: forward scheduling or due date setting, backward scheduling or due date feasibility and strike rate analysis. Both forward and backward scheduling are based on finite scheduling. (Thürer et al. 2014) Finite scheduling refers to scheduling that considers the constraints caused by e.g. capacity (Jacobs et al. 2011, p. 278). When a quotation is received a feasible due date is determined by looking forward for the earliest release date by which an order is assumed to be confirmed and all materials made available. In cases where scheduling for multiple work centres is needed, forward scheduling is done for each operation. The last operation due date is the internal due date of the order. (Thürer et al. 2014)

Backward scheduling is used to determine the feasibility of a due date requested by the customer. The latest release date i.e. the latest date an order needs to be released from the pre-shop pool to still have the product delivered on time is found by scheduling backward. If multiple work centres are needed, this is considered as in forward scheduling, only the calculation is done backwards from the given due date. In cases of overload there are three options: adjust capacity, reject the order or change the due date by scheduling, that is, rescheduling forward. Overload situations are those, where the latest release date fall before the earliest release date. (Thürer et al. 2014) WLC scheduling differs from TOC scheduling, where the scheduling starting point is the bottleneck operation and all other operations' timings are subordinated to it.

The third part of CEM, strike rate analysis, is a matrix tool to estimate the probability of winning a tender for a specific set of outcomes. The axes usually consider due date and price and are assessed using historical data. (Thürer et al. 2014) The interaction of strike rate estimation and scheduling should be considered. According to Thürer et al. (2014) in cases of forward scheduling, when the workload starts to increase so do the lead times that can be realistically offered. This in turn reduces the strike rate and, therefore, the workload. In cases of backward scheduling the actual decision making of order acceptance or rejection is passed on to the customer by giving him different combinations of price and lead time to choose from. (Thürer et al. 2014)

Order release is managed by two control mechanisms: input control that controls order release and output control which makes use of capacity adjustments to regulate the flow of work coming out of the systems. In an ideal situation the input rate should be equal to the output rate. Order release is the decoupling point between the shop floor and higher-level planning. (Thürer, Stevenson & Land 2016) Order release can be discrete, i.e. happen at pre-assigned points in time or continuous, i.e. at any time the system is working (Fernandes & Carmo-Silva 2011).

Delivery times are expected to be shorter with continuous order release due to its higher responsiveness to the system as a whole. This also should decrease the amount of orders delivered late. (Fernandes & Carmo-Silva 2011) Simulations show that input and output control should be used together to complement each other, because input control impacts more the lead time and output control the mean tardiness of a job. Tardiness refers to whether jobs are completed by or after the promised due date. (Thürer, Stevenson & Land 2016)

2.3.3 Card-based workload control

A card-based system of workload control called COBACABANA (*CO*ntrol of *BA*lance by *CA*rd-*BA*sed *NA*vigation) has been proposed to help control production. It aims to help with due date estimation and order release control. Constant work in process (ConWIP) cards control the release of orders to the shop floor (Thürer et al. 2016) but perform poorly when balancing workloads across resources is needed (Thürer, Land & Stevenson 2014). Kanban and POLCA cards control order release and orders progress on the shop floor (Thürer et al. 2016). However, kanban is not suitable for high-variety production environments and POLCA leads to blocking in cases of high routing variability, which is common to job shops (Thürer, Land & Stevenson 2014). Also, none of the three support other planning tasks. Generally, there are few production planning and control systems with cards or not that are applicable to job shops with highly customised products. (Thürer et al. 2016)

COBACABANA is a visual production control system which is based on the core principles of workload control: stabilise workload and ensure a short yet feasible allowance for the delivery time. (Thürer et al. 2016) Two types of cards are used: operation cards and release cards. Operation cards travel with the order and signal when an operation is complete, which is comparable to the functioning of a kanban card. Release cards visualise the shop floor's workload situation on a display the planner controls. (Thürer, Stevenson & Protzman 2015) The loops the cards travel are shown in Figure 10. As with order release in workload control generally (Fernandes & Carmo-Silva 2011), order release in the card-based system can also by discrete or continuous (Thürer, Stevenson & Protzman 2015).

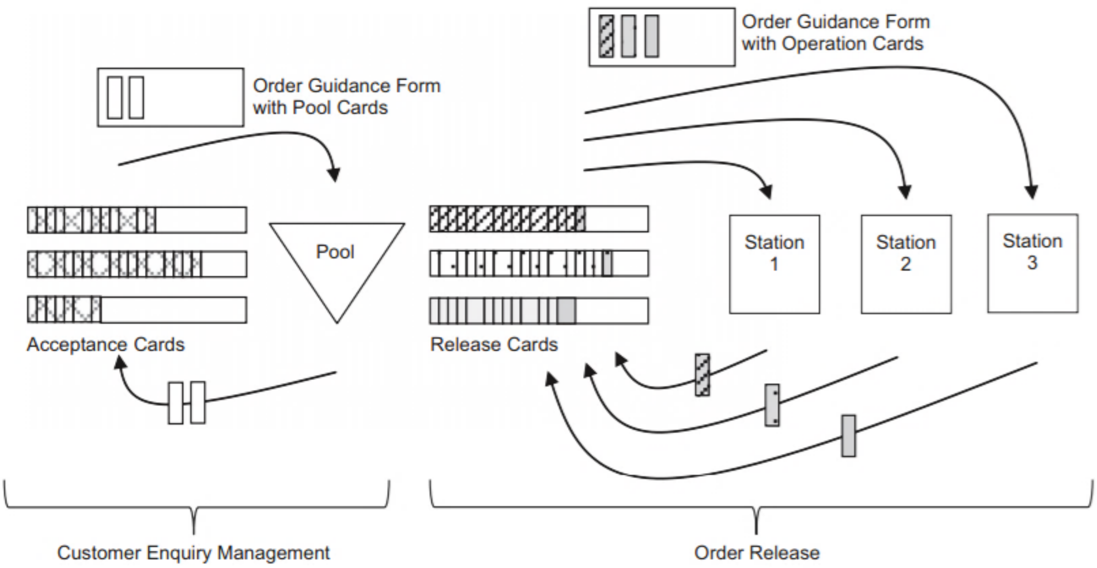


Figure 10. Integrated COBACABANA card-based solution with loops between the salesperson at customer enquiry management and order release and between the planner at order release and shop floor stations. (Thürer et al. 2016)

To release an order, the planner sorts the orders in the pool by their due date. For each operation in a job's routing exists one release card and one operation card. (Thürer, Stevenson & Protzman 2015) The release cards are sized i.e. it represents a distinct amount of workload in hours translated into a percentage (Thürer, Land & Stevenson 2014), integrating load balancing into the release decision. This way, when the planner places a release card or cards on his planning board, he can compare the workload of each station with the predefined limits and norms of each station. If the new card or cards exceed the capacity, the orders are retained in the pool. (Thürer, Stevenson & Protzman 2015)

If there is sufficient capacity, the order is left on planning board and the planner attaches the corresponding operation cards to an order guidance form which travels with the order through the workshop. Once the order an operation is completed, the shop floor returns each operation card. This is a signal to the planner to remove the matching release card from the planning board, thus making space for the next order. The planner board provides both a global overview with centralised control of the shop floor and allows for load balancing across resources. These two are the two main aspects that allow COBACABANA's control structure to go beyond traditional kanban systems. (Thürer, Stevenson & Protzman 2015)

2.3.4 Implementing workload control

According to Stevenson et al. (2011) there is literature on successful implementation of WLC, however little is given on the actual implementation process or the issues faced. Stevenson et al. (2011) themselves consider three stages for fruitful implementation of WLC: an initial pre-implementations stage, the implementation process and post-implementation. During the pre-implementation or diagnosis phase the company is assessed on its level of commitment to the project, the current business processes it has and its prior logistics performance. This may also include the evaluation of the software and hardware infrastructure the company currently has. (Stevenson et al. 2011)

The aim of the implementation process is to align theory and practice. This may require some organisational change, e.g. grouping machines into an amount of work centres that is easy to manage, improving information flow and reducing set-up times. Order release mechanisms should be selected and configured. These include but are not limited to considering bottlenecks, flow direction, capacity estimates, output control measures and workload norms. (Stevenson et al. 2011)

It is important to raise awareness and train employees at all levels to understand the logic and reasons behind the changes. If possible, this should also be extended to customers. The final post-implementation stage aims to sustain and improve control through monitoring the performance of the company and the WLC system in terms of e.g. WIP, throughput, throughput times and ease of use. (Stevenson et al. 2011)

In the case of implementing the card-based COBACABANA approach it should be decided which dispatching rule to apply, since this depends on what is considered to be most important on the workshop level. Options include but are not limited to the shortest processing time (SPT) rule and operation due date (ODD) rule. The first prioritises orders that have the shortest production lead time. The latter considers the urgency of the job. Simulations show that continuous COBACABANA is the best option for a pure flow shop. However, under continuous COBACABANA during periods when many orders come to the shop floor, there is a tendency towards SPT. (Thürer, Stevenson & Protzman 2015)

2.4 Comparison of card-based systems

Two card-based systems where discussed in chapters 2.2 and 2.3: POLCA for QRM and COBACABANA for WLC. Table 1 summarises the functioning of the cards. The positive and negative aspects of these card-based systems are given.

Table 1. Summaries of card-based systems presented with positive and negative aspects.

	POLCA for QRM	COBACABANA for WLC
SUMMARY	Push-pull signalling system where cards travel between two cells forming a loop. A returning card signals available capacity at the partner cell. Cells have dispatching lists to tell when a job is authorised to start and where it will next travel to.	Two types of cards: operation cards travel with the order on the shop floor and release cards visualise the shop floor on a board the planner controls. An operation card returned to the planner signals that an operation is complete. The planner has a pre-shop pool of orders, from which orders released based on pre-defined release rules.
+	Applicable to general job shops where material flow is multi-directional with a dominant flow direction. Good for non-repeat production.	If required material available possible to make last minute changes to orders in the pre-shop pool. Constant control of WIP, transparency and flow on shop floor. The pre-shop pool can be placed between two value adding shop floor work centres, to better control the more important steps.
-	Implementation requires 100% management support. Does not support other planning tasks, so requires other methods to address job entry and job release.	Simulations show that lead times increase when a pre-shop pool is used, because problems on the shop floor are merely relocated to the pre-shop pool. Restricts shop floor operator decision making. In practice, communication between shop floor and planner adds to the overall lead time.

2.5 Cultural dimension

2.5.1 Culture in the context of an organisation

Culture are the learned beliefs, values, rules, norms, symbols and traditions common to a group of people. These qualities are shared within a group making it unique. Culture is dynamic: it can be transmitted to others and it evolves. (Northouse 2007, p. 302) There is no standard definition for organisational culture, but it holds certain characteristics. It is holistic, that is it refers to the whole that is more than the sum of its parts. It reflects the history of the organisation where it has been created and preserved by the people who form the organisation. In some instances, it may also be difficult to change. (Hofstede, Hofstede & Minkov 2010, p. 344).

Organisational culture is acquired when a person enters a work organisation at a relatively adult age. By then a person's values are already firmly in place, and the organisational culture acquired is mostly at a superficial level in the form of practices. (Hofstede, Hofstede & Minkov 2010, p. 346) If culture is what distinguished the members of one group or category of people from others, organisational culture is what distinguished the members of one organisation from others. However, the difference lies in the fact that an organisation's culture is maintained not only in the mind of its members, but also its stakeholders. (Hofstede, Hofstede & Minkov 2010, p. 344).

The organisational culture Wärtsilä corporation promotes is a leadership culture with emphasis on high performance and operational excellence throughout the organisation. Employee engagement is promoted through "a culture of open communication, integrity and innovation". Strengthening accountability and ownership is encouraged. (Wärtsilä 2018) Leadership is "a process whereby an individual influences a group of individuals to achieve a common goal" (Northouse 2007, p. 3).

There are certain traits a person in a leading position should possess or cultivate for others to perceive him or her as a leader. Intelligence includes having strong verbal, perceptual and reasoning abilities. Self-confidence and determination create a sense of high self-esteem and self-assurance which are attributed to people who can make a difference. Integrity shows a person's trustworthiness and sociability is perceived as a sign of empathy. (Northouse 2007, pp. 18-21) In the context of improving production planning and control practices it could be said that the person responsible for a specific product line is the leader of the order processing process.

The basic condition to taking responsibility and carrying out a leadership role is knowing your responsibilities. For planners to deliver a product on time this requires answering the what?, when?, where?, how? and who?-questions and making informed decisions based this. The questions are elaborated upon in Figure 11.

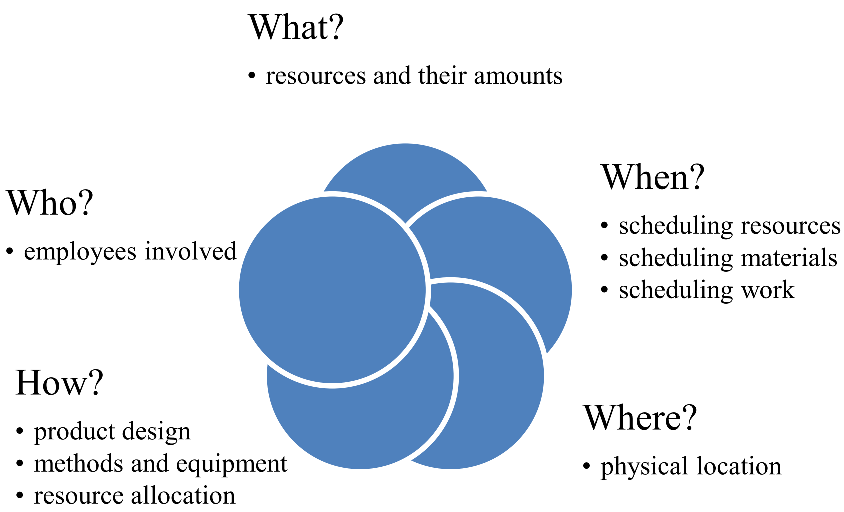


Figure 11. Key decisions made by an operations manager (visualised from Stevenson 2015, p. 17).

In Wärtsilä there is a continuous focus on competence development and performance excellence, which inadvertently involves implementation of changes within the organisation (Wärtsilä 2018). Implementing new ways of working is not only about charting a new process but getting people to take them in as a part of their culture. Worth considering are the two paths that lead to results: the guiding path and the driving path, shown in Figure 12. Strategy is the formal logic orienting people to the company's goals. Culture directs activity through shared assumptions and group norms which are anchored in unspoken behaviours, mindsets and social patterns. (Groysberg et al. 2018)

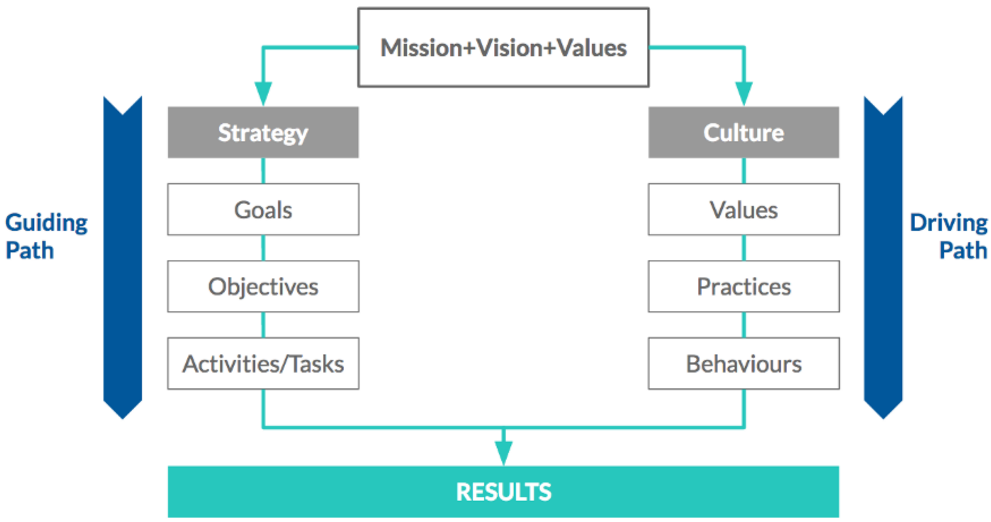


Figure 12. The challenge of building organisational alignment. (Candi 2017)

Another aspect to consider when implementing new ways of working is resistance to change ingrained into human behaviour. However, Lawrence (1969) points out that the causes for resistance are usually blind spots and attitudes which employees have for the technical aspects of new ideas. The key is to understand the root cause for the resistance and get employees involved to “participate” in creating and carrying out the change. Management’s role is to deal constructively with employees’ attitudes. (Lawrence 1969)

2.5.2 Culture in the context of a country

Implementation will be distorted by the local adaptations of the global organisational culture. The cultural context of the country should be considered. National culture is part of a person’s mental software acquired during the first ten years of his or her life (Hofstede, Hofstede & Minkov 2010, p. 346). The Dutch Geert Hofstede (b. 1928) has conducted extensive comparative research on cultural differences, which he combines under five dimensions: masculinity versus femininity, uncertainty avoidance, individualism versus collectivism, power distance and long-term versus short-term orientation (Hofstede, Hofstede & Minkov 2010, pp. 31-38). The results for each country are given as an index with 100 showing a strong representation of a given dimension in the culture. The index values for China are plotted on a radar in Figure 13. The values for Finland are given as a comparison.

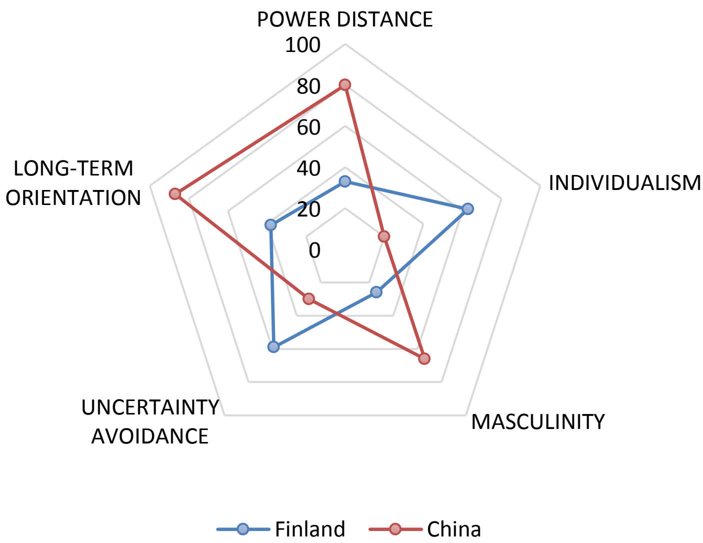


Figure 13. The evaluation of China and Finland by Hofstede’s dimensions. (Hofstede, Hofstede & Minkov 2010, pp. 57-255)

High power distance means people in the countries accept and appreciate inequality yet believe power is regulated by a sense of obligation (Hofstede, Hofstede & Minkov 2010, p. 80). Hofstede, Hofstede & Minkov (2010, p. 237) suggest this originates from Confucius’ teachings, that the stability of society is based on unequal status relationships between people. A leader is expected to be protective of his or her own leadership, team-oriented and people-oriented. Though the leader is seen to a certain extent as inspiring, his subordinates are not invited to be involved in goal setting or decision making.

(Northouse 2007, pp. 316-317) In turn, low individualist i.e. high collectivist societies avoid direct confrontations and there is a prevalence of high-context communication. Management-wise managing in high collectivist societies is about management of groups, which means that incentives and bonuses should be given to the group. (Hofstede, Hofstede & Minkov 2010, pp. 113-121)

The dimension of uncertainty avoidance refers to the extent to which members of a culture see ambiguous or unknown situations as threatening. In low uncertainty avoidance societies employers are changed more often than in high uncertainty avoidance societies and people work hard only when needed. (Hofstede, Hofstede & Minkov 2010, pp. 191-217) Long-term orientation refers to promoting virtues oriented toward future rewards, especially perseverance and thrift. In long-term oriented societies people are willing to subordinate themselves for a purpose. (Hofstede, Hofstede & Minkov 2010, pp. 239-243)

Hofstede, Hofstede & Minkov (2010, p. 316) also write that organisations with high power distancing support political over strategic thinking. When it comes to planning and control, the higher in the hierarchy one moves the less formal planning and control becomes. Yet, less trust is placed on subordinates than in a low power distancing culture. Low uncertainty avoidance organisations do not tend to support a need for detail in planning while seeing more information as relevant than in a high uncertainty avoiding culture. (Hofstede, Hofstede & Minkov 2010, p. 316)

Groysberg et al. (2018) talk of a culture evolving flexibly and autonomously to answer changing opportunities and demand. But in a collectivist organisation with high power distancing it seems like there has to be a trigger coming from the top for change to happen. As Hofstede, Hofstede & Minkov (2010, p. 217) people work hard only if there is a need, so that need must come from someone on the next level of the hierarchy. Thus, any change carried out at WSZ requires that the management team is fully supportive of it to further push it onto their subordinates.

2.6 Feasibility of theories discussed in the context of WSZ

Three frameworks for managing production planning and control were discussed: aggregate planning coupled with TOC logic in scheduling, quick response manufacturing and workload control. The latter two had card-based control systems. Also, a description of the cultural context was given. Next the applicability of the frameworks to the main question, "*How to organise production planning and control at WSZ so that it is responsive to the needs of a multi-product factory?*", will be discussed. Summaries of the theoretical frameworks along with challenges WSZ may face in implementing them are given in Table 2.

Table 2. Summaries of theories discussed and implementation challenges WSZ may face.

	AGGREGATE PLANNING WITH TOC SCHEDULING	QUICK RESPONSE MANUFACTURING	WORKLOAD CONTROL
SUMMARY	Aggregating production demand quantities to level of resources over a fixed planning horizon. Subordinating production scheduling to bottleneck capacity.	Reducing operational and production lead times. KPIs based on critical-path duration. As a pre-requisite organisation structured into QRM cells i.e. operational teams.	Levelling workload to capacity to ensure high delivery reliability. Systematising planning activities by linking process, material and capacity planning.
CHALLENGES FOR WSZ	Requires a forward-looking attitude. The current bottleneck, material availability, is outside the factory.	Autonomous operational cells unrealistic in the current cultural context because they require discipline and taking responsibility.	Managing and making frequent changes to buffers time-consuming and has a high risk of mixing up operations.
CARD-BASED SYSTEM EVALUATION FOR WSZ	n/a	POLCA designed for production with complex routing, which is not the case at WSZ.	COBACABANA can be applied for WSZ, but risk that a pre-shop pool will lead to longer lead times.

Aggregate planning is useful for organisations that experience fluctuating demand or capacity. WSZ faces both. If an aggregate planning framework were used at WSZ, the chase strategy would have to be followed due to its MTO environment. Hiring part-time outsourced workers is already in use to manage human resource capacity on the shop floor. Aggregate planning would require WSZ to be forward-looking with its forecasts. For some product lines getting accurate forecasts may be difficult, however, planning ahead could help WSZ get rid of unsold products that need to be scrapped. Using up stocked products would decrease tied up capital. Aggregate planning would also take into account the resource capacity during holidays.

Scheduling under aggregate planning emphasises on setting realistic due dates, focusing on bottleneck operations and lot splitting. Setting credible due dates coupled with clear prioritisation rules would help solve the constant urgency feeling currently present in WSZ operations. Agreeing on reachable due dates and then achieving them would improve the relationship between WSZ and the product company, which would also ease the communication between the product company and the end customer. When scheduling STC production it is realistic to find the bottleneck to which everything else can be subordinated. Lot splitting is already in use in STC production by pre-assembling the pump and control panel before starting the top order assembly.

Implementing quick response manufacturing with its emphasis on lead time reduction would improve WSZ's competitiveness. Lead time reduction throughout the order processing operations at WSZ should have a positive impact on OTD performance. Additionally, QRM is designed to succeed in the MTO environment WSZ works in. A positive response time spiral analogous to the response time spiral shown in Figure 8 was created and is presented in Appendix 2. Having short lead times would improve flexibility. Implementing QRM would improve production PPC practices at WSZ and answer both current, but especially, future needs.

However, a pre-requisite to implementing QRM is the need to change organisational structure from top-down control to cellular team ownership. This type of structure requires proactiveness, self-leadership and a deep sense of responsibility. Based on what was discussed in Chapter 2.5.2 a cellular organisation does not seem realistic in a high power distance society like China. In this case the culture of the country is bound to override the culture the organisation is trying to impose. Thus, from, a feasibility perspective, it is not realistic to implement QRM at WSZ. Yet, time-based thinking and lead time reduction goals should be promoted.

Workload control emphasises a better use of buffers to handle variability. WSZ already has the three buffers, inventory, capacity and lead time, in place. However, making them changeable variables does not seem like an easy task in the current context of WSZ. Also, COBACABANA sounds like a very complex system for handling the relatively simple STC production. At WSZ planners are responsible for 1-2 product lines, in which case if they did use COBACABANA it would not reflect the situation of the whole factory. Implementing card-based workload control would require restructuring the order management department or redefining the responsibilities of the order management manager.

Some aspects of workload control are worth considering implementing into WSZ's operations. Firstly, forward scheduling to find feasible due dates would put emphasis on giving realistic due dates. Scheduling forward would let WSZ to consider all factors of production and setting an achievable due date based on factor availability. Workload control considers different order dispatching rules, among them ODD. Implementing any kind of prioritisation rules should help WSZ carry out tasks in a systematic manner without the constant feeling of urgency currently present. In the MTO environment ODD is the rights option since it emphasises OTD.

3. CASE APPLICATION

3.1 Current state

3.1.1 Overview of the STC product line

The STC product line consists of sewage treatment plants (STCs) and retrofit sewage treatment plants (RTCs). At WSZ both are combined under the name STC regardless of whether the sewage treatment plant is retrofit or not. The term STC is used throughout the thesis to indicate both categories. For reference photos of STCs can be found in Appendix 3. There are twenty types of STC produced at WSZ. All can be fitted with one or two ejectors, which raises the number of configurations to sixty. However, looking at the STCs invoiced during the 19 months studied, STCs 01, 02, 03, 04 and 06 cover 80% of products invoiced. In production STCs are divided into small, medium and large based on their size. The hierarchy between STC product lines and STC product sizes and types is shown in Figure 14.

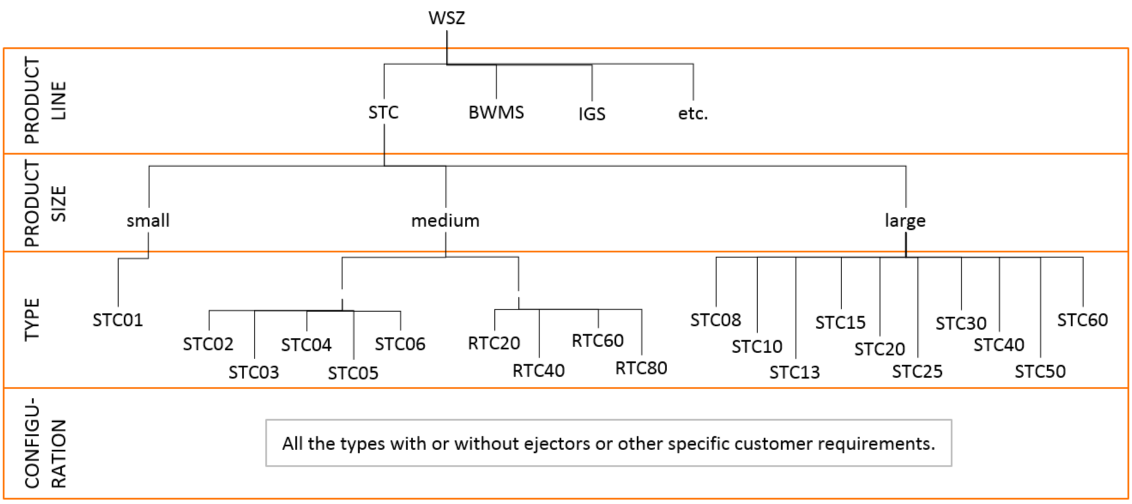


Figure 14. A hierarchical representation of product lines and STC product sizes and types.

The assembly time of an STC top order, that is assembly order after painting, ranges from three to six days. For products with an ejector fitting 2-3 days are added to the assembly time. The production lead time of the top order refers to the time from the moment the top order is released to production to the point it is invoiced. Basically, it is the time for IQC, FAT and packing added to the assembly time. The assembly and production lead times of the top orders by STC size are shown in Appendix 4. STC order management follows the basic order processing shown in Figure 2. More details on the STC order processing process are given in appendix 5.

3.1.2 Summary of issues

For qualitative data unstructured interviews were carried out. For quantitative data STC products invoiced during the 19 months prior to starting the research were studied. The data analysis is given in Chapter 3.1.4 with further details in appendix 6. A current reality tree was created, shown in Appendix 1 and discussed in Chapter 3.1.3. The following issues came up as causes leading to bad on-time delivery performance:

- Lack of technical documentation to start engineering.
- Material shortages in production.
- Lack of shipping instructions needed for delivery.

Based on the current reality tree, the root cause of all the issues the lack of systematic production planning and control. Additionally, from the qualitative and quantitative data the following issues and causes for issues came up:

- Late material delivery from supplier.
- Quality issues in material.
- Lack of human resource capacity during production.
- High variability in monthly quantities of invoiced products.
- Over 80% of products delivered late.
- Production lead times significantly longer than planned.
- For over 90% of products production finished later than planned.

3.1.3 Qualitative data – issues from unstructured interviews

For qualitative data on the reasons for late deliveries a current reality tree was constructed based on unstructured interviews with the employees at WSZ. The current reality tree is shown in Appendix 1. The issues raised can be grouped under different responsible parties: the customer interface, which in this case refers to the product company, engineering, material management, production and planning. The product company affects negatively on-time delivery by being slow with sending the technical documentation, making mistakes in the part lists or requesting changes in the EBOM after the freezing point when material purchasing has already been started. If the technical documentation is late, material purchasing is started later than planned, which in turn means that material is available for production later, thus pushing the delivery date. There are also cases when the product company places orders which need to be produced at a very tight schedule, which WSZ is unable to observe.

In-house engineers affect negatively on-time delivery if they make mistakes in the PBOM or issue an engineering change request (ECR) to change a components or components in the EBOM given by the product company. However, there do not seem to be many cases of the former and the latter is used more to exploit components that are already available, which reduces the amount of materials that need to be purchased decreasing the risk of late delivery due to not having all the material available for start of assembly.

The material management team is the link between WSZ and the multiple suppliers. If components with a long purchasing lead time are late eating up the buffer the planners use when agreeing on a delivery date with the product company, the product cannot be delivered on-time. Purchase orders on components are placed based on dates SAP calculates and for the most part are placed on time. However, there are limited sanctions towards suppliers who deliver late. When a supplier tells he will be late with a delivery, warehouse checks the material availability only of those components that are needed immediately in production.

Sometimes material arrives on time, but does not pass the incoming goods quality control, in which case it is returned to the supplier for rework with comments on what went wrong. Reasons for rejection are stored in a spreadsheet, however, no root cause analysis is carried out to see if there are systematic mistakes suppliers do. Sometimes, due to limited human resources in the warehouse or the buyer team, material handling in the warehouse and supplier chasing is slow, which again affects material availability and, thus, the possibility for on-time delivery. There are also cases, when the main STC material, the tank arrives on time or even a little early taking up floor space, but the other material is not available or has not been warehoused.

The biggest issue found in production is a large amount of WIP. Assembly is started before all material is available, as planning pushes production to start to meet the delivery date. However, once assembly with the available material is finished, the sewage treatment system is left to stand in assembly to wait for the missing parts. Firstly, this takes up assembly space blocking the assembly of an STC that has all the material available. Secondly, it is demotivating for the workers to be unable to properly finish the task given to them. Also, when material finally is available, there may not be available workforce to finish the assembly, because the production department did not have the information to plan ahead and divide its resources.

Based on the current reality tree, the root cause of all the issues the lack of systematic production planning and control. This falls under the responsibility of planning, which, by definition (Stevenson 2015, p. 517), refers to the collective set of actions related to integrating information on forecasts, orders, production capacity, on-hand inventory quantities, bills of material, WIP, schedules and production lead times. In the make-to-order environment, the primary activity is controlling the progress of customer orders to meet the promised delivery dates. Any engineering or manufacturing changes must be related to the master production scheduler to determine their impact on the final delivery to the customer. (Stevenson 2015, p. 56) At WSZ the master production scheduler for sewage treatment system production is the planner responsible for the product line. Thus, to improve on-time delivery, changes must be made in the way planning manages orders.

3.1.4 Quantitative data – issues from data analysis

Data for sewage treatment systems invoiced during the 19 months prior to starting the research was collected to analyse and answer the questions raised in Chapter 1.4. During the period studied a total of 217 products were invoiced, which means on average 11-12 products monthly. Invoiced products were studied, because based on the order processing it can be safely assumed that all product invoiced have received shipping instructions and have left WSZ. It should be noted, that because some sales orders have multiple products, the unit of analysis is one STC product. The most common STCs invoiced were STC01 and STC02, covering 40% of the volume. Further distribution of volumes by type are shown in appendix 6A.

To see the actual rate of production Figure 15 was created. It shows a fluctuating rate of invoicing, with some months like June 2017, when only three products were invoiced against September 2017, when 23 products were invoiced. The increase in number from products invoiced in March to those invoiced in February can be explained by the by smaller production amounts in the latter month due to Spring festival. Otherwise national holidays or other festivities do not seem to have an effect on the monthly invoice amounts, which shows clear variability in the processes at WSZ. The columns are colour-coded to see the distribution of production of STCs by type.

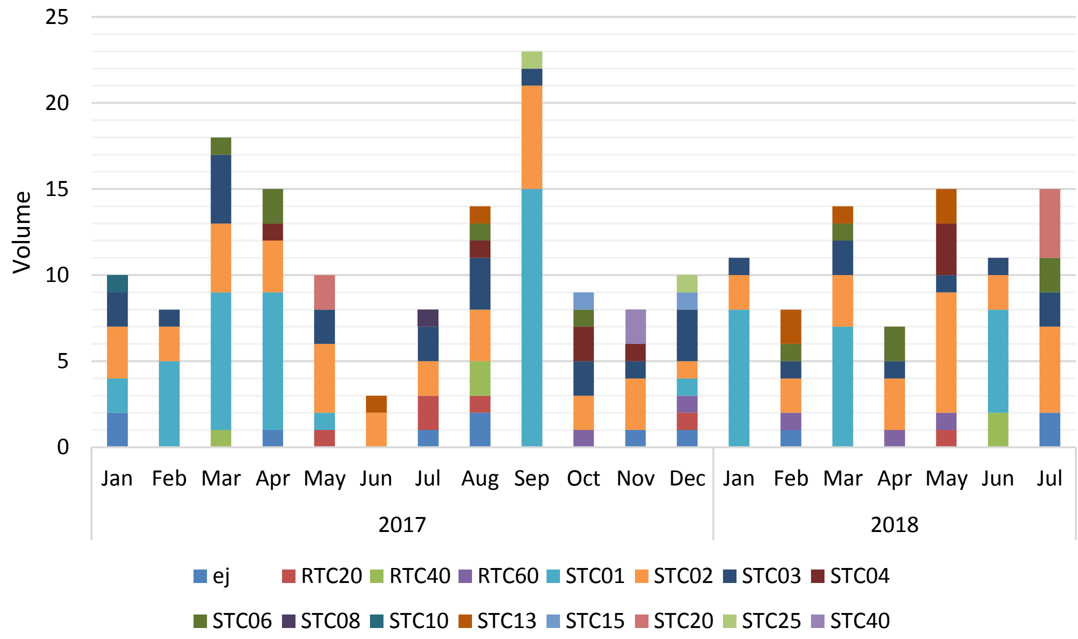


Figure 15. Monthly distribution of invoiced STCs during the studied nineteen months.

The data was further analysed to see, whether the number of products released to production, finished and invoiced follow a pattern on a monthly level. The details are given in Appendix 6B. It was noticed that there was great variability. Products released into production are finished much later than expected when knowing kitting and assembly times.

Invoicing also lags behind production finishing showing again a lack of discipline in the order processing process of STCs. To see whether this influences on-time delivery Figure 16 was made. A product is considered to be on time if WSZ ships it on the day requested by the product company. A detailed discussion on delivery date holding is given in Appendix 6C.

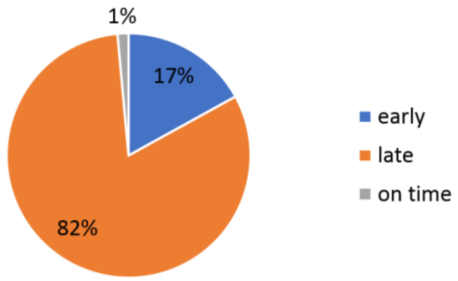


Figure 16. On-time delivery performance of STCs during the 19 months studied.

To find the cause of on-time delivery performance variability in the production lead times was studied. The in-house definition for production lead time is the time from the point when the product is released to production to the date it is shipped. In SAP the first is the "release date (actual)" and the latter is actually the invoice date, since invoicing is done as soon as the shipping instructions are received. This definition of production lead time does not consider situations where the reason for a lengthened production lead time is not WSZ's fault. For example, the customer may agree on an FAT date very far in the future, but the time it waits as a ready product is still considered to be part of the production lead time. If an ECN requiring additional components is issued, the time waiting for supplier delivery adds to the production lead time. Also, the product company may be slow with issuing the shipping instructions, which again increases the production lead time, even though the product is ready and packed.

To mitigate the reasons for tardiness from outside sources a "pure" production lead time is calculated. For this the start date is again set to be the date the product and its components were marked to be released into production in SAP and the end date is the date marked into SAP as the actual finish date. When the product is released it is first kitted, the kits moved to the production area and then the product assembled. The actual finish date should be marked into SAP after this. The studied products were divided into five categories based, firstly, on their size and, secondly, on their planned "pure" production time. The way the planned "pure" production time was calculated is shown in Appendix 7. The five categories are small STC, medium STC, RTC, large STC and medium STC with ejector fitting. The sample size for each category is different, because the production quantities for different product types during the period studied are different. The distribution of "pure" production lead times for products in the five categories are shown in Figure 17 and by orders with reference to the planned lead time in appendix 8.

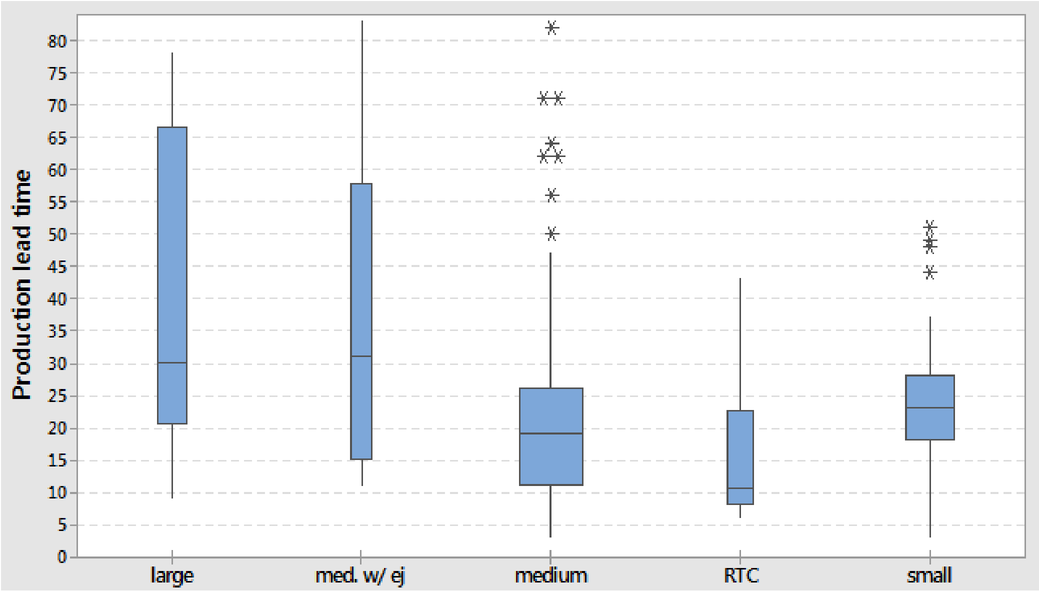


Figure 17. Distribution of ”pure” production lead times of STCs by size.

The planned reference “pure” production lead time is 11 days for the large STC, 11 days for the medium STC with ejector, 10 days for RTCs and 8 days for small and medium STCs. Before analysing Figure 17 it is worth noting two things. Firstly, the lead time shown is the number of days between the date the top order is marked in SAP to have been released into production and the date production was marked as actually being finished, including weekends. However, WSZ’s work week is five days, and work is done on weekends only in urgent situations. Since WSZ has issues with on-time deliveries, it is not unusual for shop floor employees to be overtime on weekends, but it is unclear how much weekend work was used on the products studied. To balance out the additional weekend days 1-3 days were added to the planned production lead time.

Secondly, both small STC and medium STC production lead time data had a few outliers showing a lead times of over 110 days. These were deleted from the graphs, so the scale would be clearer. From the graphs in Figure 17 it can be clearly seen that all STC sizes have variability in their lead times, though RTC performs the best. This may be due to the small sample size. Small and medium STCs manage to be finished within 30 days from being released, though both have products with lead times nearing two months or more. Though RTCs perform better, those that have a long lead time stretch over a one-month lead time. Over half of the studied large STC products had over a month-long lead time, a third over two months, when the planned lead time routed into SAP is half a month. For STCs with ejector fitting, again, the actual lead time stretches clearly beyond the planned.

The mean of actual production lead times for the different categories was calculated and then compared to the planned production lead times. In two cases the mean for the actual production lead time was over twice as long as the planned production lead time. The values are shown in Table 3. When comparing the numbers two things need to be taken into account. Firstly, the sample size for the different categories is very different. Secondly, using a mean is more of a guideline to of what the situation is, but lacks in accuracy in cases with a lot of variability and outliers. This is why the most serious cases of the latter have been removed from the data set.

Table 3. Difference between planned and mean of actual "pure" production lead time in days.

	planned	mean of actual	**days longer**
small STC	8	24	**16**
medium STC	8	23	**15**
RTC	10	16	**6**
large STC	11	40	**29**
medium STC w/ ejector	11	36	**25**

A next logical question is whether production is finished as much later as the production lead time stretches. This was calculated as the difference between the actual production finish date and the finish date scheduled by SAP based on the delivery date requested by the customer. The day-wise distribution is shown in Appendix 9 and the week-wise distribution is shown in Figure 18. Assembly finishing timeliness shows an otherwise normal distribution, but with a long tail, highlighting the existence of products finished a lot later than planned. However, most products finish at most a month later than planned.

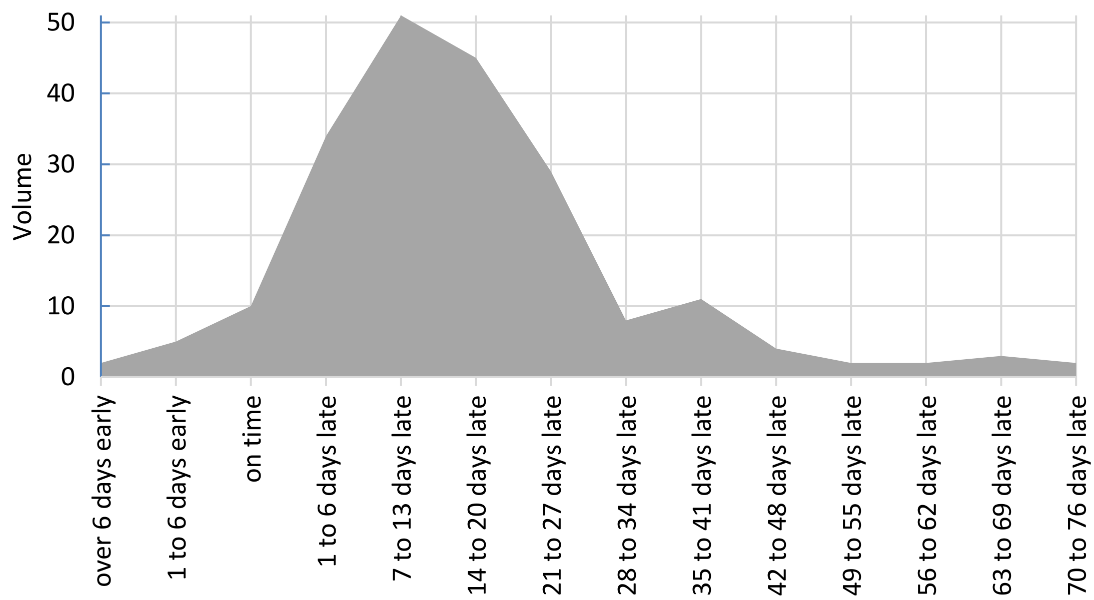


Figure 18. Distribution of assembly finishing timeliness.

Table 3 was extended with the mean of lateness for the late products, shown in Table 4. In most cases products for each category were later than the extended production lead time made them. Yet, no judgement can be made to the extent the longer lead times influenced the lateness of production finishing. Firstly, the production could have been marked to be finished later than it was. Secondly, there may have been issues earlier in the process before the product was released into production. Thus, increased production lead time is not the only explanation behind production finishing late.

Table 4. An extension of Table 3 with mean of lateness in days.

	planned production lead time	mean of actual production lead time	**days longer**	**mean of lateness**
small STC	8	24	**16**	**19**
medium STC	8	23	**15**	**14**
RTC	10	16	**6**	**13**
large STC	11	40	**29**	**35**
medium STC w/ ejector	11	36	**25**	**28**

The next logical step would be to compare the planned start of assembly dates to the actual ones, which, as explained above, are unfortunately not collected. Comparing the planned and actual release dates was deemed pointless, because orders are aimed to be released based on the date SAP schedules them to be released regardless of whether material is available or not. One reason for bad on-time delivery performance in the current reality tree, shown in Appendix 1, was ECNs raised after material purchasing has started. For the products studied one product had an ECN raised after material purchase and after FAT, with another nine having an ECN raised after FAT. Thus, though all these products were finished late, ECNs were not the reason.

3.2 Future state

3.2.1 Outline of future state

The long-term goal is for WSZ to have a 100% OTD performance with the issues raised in Chapter 3.1.2 fixed. In the intermediate-term the goal is to improve production planning and control practices in the STC product line to be:

- Based on taking **responsibility**, which includes finishing the tasks assigned and taking care that issues are really solved, not just pushed onto someone else.
- **Forward-looking**, so actions are proactive, and issues are solved before the need for firefighting. This includes prioritising orders and, therefore, tasks.
- **Disciplined**, meaning that the implemented practices' usage will be sustained without slipping into old ways of doing.

A future reality tree was constructed as one of the logical tools shown in Figure 4. It is shown in Appendix 10. It shows how systematic production planning and control will lead to on-time delivery, the final goal. Systematic production planning and control includes both forward-looking production planning and production being under control.

Forward-looking production planning includes production, material management and customer perspectives. Production-wise this means that production capacity and shop floor availability are factored into scheduling. On the supplier side being forward-looking refers to giving suppliers realistic forecasts, so they can plan their own capacity in advance. Transparency towards suppliers should also help with suppliers seeing WSZ as a serious customer. These both points would lead to better on-time delivery performance from their part. The customer perspective refers to promising the product company realistic due dates that hold.

Production being under control refers to what Jacobs et al. (2011, p. 56) calls the main activity in the make-to-order environment, that of controlling the progress of customer orders to meet the promised delivery dates. This means that the planner should be informed on the status of the orders he is responsible for at all times, which results in him being able to communicate accurate information to the product company. Being informed on the status also refers to following material availability, as this is the main production enabler WSZ has issues with. Even in cases when the supplier is late it is possible to foresee the disturbance in material availability, take action to secure material to be available by the time assembly is set to start and communicate to the product company if material lateness will push planned SoA so far forward, that it eats up all the buffers added to the process. Transparent and timely communication coupled with realistic delivery date setting increases the level the product company’s trust in WSZ, which ideally would lead to the product company being stricter about its own processes. These include making changes to the EBOM only before the freezing point and sending WSZ shipping instructions as soon as they are requested.

All the above should lead to having both assembly workers, floor space and material available for the SoA which means there are no barriers to the product flowing through production. This means that the FAT date agreed and confirmed early on, because planning was forward-looking, holds and the product does not stay in WIP to wait for FAT. In a normal situation, where no ECNs have to be raised after the FAT, the order is closed as planned and the product delivered on time. Even in case ECNs are raised after FAT, the product can be considered as “delivered” on time, since production was finished as planned.

3.2.2 Benchmarking best practices at DCT and DCV

To get a more comprehensive understanding of what production planning and control can be on a practical level best practices were benchmarked from two other Wärtsilä factories: Delivery Centre Trieste (DCT) in Italy and Delivery Centre Vaasa (DCV) in Finland. Both produce engines for all three business lines shown in Figure 1. Both delivery centres used to have the following issues:

- Last minute design changes.
- Material shortages in production.
- Bad OTD performance.

To combat last minute design changes and for the sales order to flow through the order processing operations smoothly three freeze points were set to stabilise the process. Because engineers at DCV are also responsible for making the engine design and EBOM, the first is a design requirement freeze after which no additional engineering demands can placed on the order. This gives engineers the possibility to create the design without disruptions. The next freeze point is a design freeze after which no changes can be made to the design enabling sourcing and purchasing to carry out their tasks. The last freeze is the start of assembly freeze, with the aim to cut down disturbance in sourcing, purchasing and internal logistics.

To tackle material shortages in production emphasis was placed on being forward-looking and managing production enablers, which for DCV and DCT are product design, material, capacity, tools and processes. For this purpose, at DCV the delivery manager, a position comparable to that of an order management manager at WSZ, organises a weekly meeting where the production enablers for orders with start of assembly in the upcoming eight weeks are systematically gone through. Emphasis is place on the upcoming three weeks, because any unsolved issues in that period may result in a need to delay start of assembly. The additional five weeks is also checked, because the earlier issues are noticed, the more time there is to react and fix the situation. Before the meeting on production enablers operative purchasing has its own meeting where they to check material delivery and availability for the upcoming eight weeks, so informed decisions can be made at the former meeting.

By taking care of production enablers the delivery centres automatically improved their OTD performance. Additionally, for production planning and control both factories use a tool called “slot planning”. In production management theory slots are compared to empty shells organised around a bottleneck resource and identified in several dimensions e.g. workload, space or machine functionality (Hinckeldeyn et al. 2010). At DCV the slot size is based on a combination of available production capacity and forecasted demand, with emphasis on the former. Thus, for changes in demand in the long-term production capacity can be adjusted and the number of available slots increased or decreased accordingly.

A slot is reserved, when sales informs planning of a possible sales order. In SAP it is marked as a notice of contract. When reserving a slot the planner calculates backwards from the start of assembly of the top order to have preliminary dates on when engineers need to have design requirements to make the EBOM, when is the design frozen to start purchasing and when the product will be ready for FAT and delivery. Standardised long lead time items are purchased based on the forecasted BOM attached to the reservation. Engines are engineered in a way, that same engine types use the same long lead time materials to ease purchasing and forecasting towards suppliers. Thus, even in case of a cancelation these materials can be used in another engine of the same type.

When a sale is made the slot and the dates mentioned above are confirmed. The FAT is reconfirmed a few weeks before start of assembly of the top order, which is roughly a month before the FAT date. Both delivery centres use a spreadsheet for slot scheduling, supporting it with SAP. Neither found separate slot planning software available on the market to be flexible enough or easy to integrate with SAP.

3.2.3 Necessary conditions

For production planning and control at WSZ to be based on taking responsibility, being disciplined and forward-looking certain conditions need to be met. The basic condition to taking responsibility is knowing your responsibilities. Planners should understand that they are the operations managers to the product line they oversee and embrace their role of informed decision makers when it comes to delivering a product on time. They answer the what?, when?, where?, how? and who?-questions elaborated in Figure 11.

Discipline or the lack of it originates from the culture prevalent in the organisation. As Hofstede, Hofstede & Minkov (2010, p. 217) noted people work hard only if there is a need, which can be understood as people being intrinsically undisciplined. WSZ being in China the importance of management being disciplined and enforcing the continuing usage of implemented practices cannot be underemphasised. In a high power distance society action is taken when an order from above is given. Thus, discipline and sustaining a forward-looking mindset comes from measures management takes and places onto its subordinates.

In order to make *informed* decisions, as Stevenson (2015, p.17) emphasises, planners need to communicate with different stakeholders, which answers the who?-question. For the order specifications the planner should communicate with the customer, which in the case of STC is the product company. To answer what?, when? and how? the planner has to communicate both with engineering and material management. In the case of STCs where? is a specific area on the shop floor. Communicating with production is important when answering human resource and work scheduling. Logistics is the stakeholder that will be replying about ready product delivery. To enable the primary activity of the make-to-order environment, that of controlling the progress of customer orders to meet promised delivery dates (Jacobs et al. 2011, p.56), communication with stakeholders is essential. The stakeholders are summed up in Figure 19.

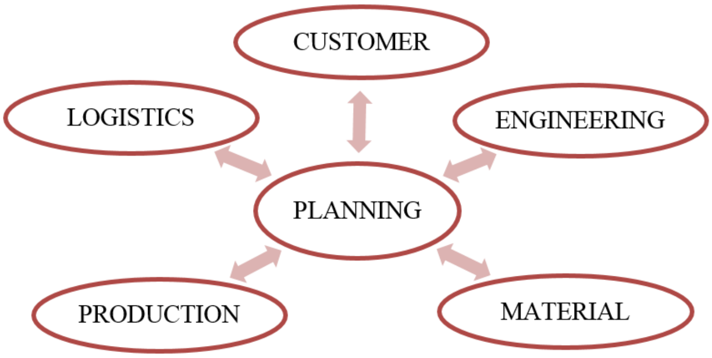


Figure 19. Stakeholders with whom planners should actively communicate.

Benchmarking from DCT and DCV it is suggested slot planning be implemented. For this the logic behind scheduling must be changed. As elaborated in Appendix 5 scheduling is currently done based on the EXW date. In practice this means that instead of planning communicating to production that a product should be released to production on a particular date, they communicate the date production should be finished, effectively taking over production management for which exists a separate responsible department at WSZ. To remove this unnecessary responsibility off the planner, scheduling should be based on the start of assembly date. EBOM readiness, material purchasing, material availability and material picking should be calculated backward from this date and FAT with the delivery date should be calculated forward.

The main pre-requisite for slot planning to work is that all order processing operations shown in Figure 2 run the way they should. WSZ promises to deliver a product on time in return to the product company providing on time product specification information. After this information is received it is up to WSZ to have all the internal processes working. The biggest issue behind on-time delivery problems is material availability. The first step is to have products flowing through assembly.

For this full-kitting should be implemented. Full-kitting means that production can start only when all material required by the order is available (Kern 2018). Earlier in 2018 full-kitting was tested and implemented with positive results in control panel production at WSZ. For STC production it would mean that the top order should have all the material available before painting and then assembly can be started. This should lead to production being able to finish all work in the planned time and decrease the variability currently seen in production lead times. Full-kitting would also solve the problem of high amount of WIP created by material shortages in production.

To have product flow through assembly and be ready by the promised delivery date all the production enablers need to be available by the start of assembly date tied to the agreed slot. On the one hand, this means that suppliers have to deliver on time. On the other hand, this means that material needs to be purchased early enough and suppliers should be given forecasts based on which they can better plan their processes. At the end of the day WSZ is the one responsible for having all the factors of production available, not the suppliers, so following material availability and planned delivery dates weeks before start of assembly is a must. Again, the need to take responsibility, be forward-looking and disciplined arises. It is suggested similar weekly production enabler meetings as in DCT and DCV be taken into practice.

In order to purchase the material, especially long lead time material, purchasers need to know what material to purchase. This comes directly from the PBOM made by in-house engineers from the EBOM coming from the product company. Thus, another pre-requisite is to get the technical documentation from the product company by the date requested by WSZ calculated backward from the confirmed slot reservation. This also requires holding on to the freezing point, communicated to the product company, after which no changes can be made to the engineering, so material purchasing can happen without disturbance.

3.2.4 Information needed

The information needed is related to being forward-looking and implementing full-kitting with slot planning. As Stevenson (2015, p.17) emphasises to make good operations related decisions one needs to be informed. This means sharing information received by e-mail and keeping SAP data accurate and up-to-date. Transparency and communication play the major role in informed forward-looking planning.

To see through the order from purchase order receival to the shipment of the ready product, the planner must know the overall process and the lead times for each step. He should also be informed on the lead times for the same steps but different types of STC including understanding the PBOM-structure of the products and the rough production process of STCs. Collecting data on actual start of assembly would allow to see the real assembly lead time from start of assembly to finish of assembly. Firstly, this would make scheduling more informed. Secondly, if there is variability in the lead times, root cause analysis can be carried out.

To create a slot planning tool first it is necessary to know what is the bottleneck or constraint that will define the number of available slots per week. In this way slot planning is tied to a TOC mindset, where the bottleneck determines the overall capacity of the system (Goldratt 2014, pp. 164). Based on the experience of the mechanical production supervisor who overlooks STC production for STCs the bottleneck is mechanical working capacity. In the factory there are eight mechanical workers who can work on any of the product lines' products, out of which two are usually allocated to work on STC mechanical assembly.

To calculate realistic schedules after reserving a slot purchasing and production lead times need to be known. For the former especially long lead time component purchasing lead times are important. For STCs the long lead time item is the tank and for some STC sizes also the pump and blower. The availability of these materials should be especially followed for production to start in the agreed slot. It is worth noting that the material with the longest purchasing lead time defines the overall lead time from sales order receival to ready product delivery.

As was discussed in Chapter 3.2.3 for assembly to start in the agreed slot all material needs to be available. Since there have been issues with material on-time delivery there is a need to collect accurate information on supplier OTD. Currently there is a supplier OTD key performance indicator (KPI) in place, which shows a near 100% OTD performance. When studying the way KPI is calculated it was found out that in following corporation-wide KPI outlines it measures the suppliers latest confirmed delivery date against the actual arrival date without considering the date WSZ requests the material to arrive at the factory nor the first date the supplier confirms he will deliver. So, data is collected on the suppliers, but not the right data needed to make informed decisions. Having the right data at hand would allow WSZ to focus on the suppliers delivering late.

3.2.5 Potential issues and their solutions

When implementing anything new obstacles are bound to arise. Some are unforeseeable, and they will need to be solved and managed as they arise. Other risks can be identified, which means that possible solutions can also be conjectured in advance. The foreseeable risks can be divided into the human factor, operational activities and information systems related.

For the human factor there is bound to be resistance to change. People see change as more work, so there is a need to emphasise that new practices are about shifting not expanding the workload. The goal is to be have people more proactive in the early stages of the order processing operation, so as to not tie valuable human resource capacity to last minute firefighting tasks. In the long-run this will decrease the amount of stressful workload by doing things earlier in a structured way.

From the operational perspective when new practices are implemented it is very likely that employees will lapse into old ways of working unless there is someone overseeing the following through. One way to have employees more interested in new ways of working is have them participate in decision making situations when new practices are planned and carried out. However, as discussed in Cchapter 2.5.2, in a high power distance country like China subordinates do not expect to be involved in goal setting or decision making, which may lead to them being passive even when asked for an opinion or criticism towards new practices. There is a risk that if they are not inspired by the leader or feel he or she is not on top of what is being done they will become negligent in carrying out the implemented practices. This puts emphasis on management being disciplined enough to put pressure on subordinates' discipline.

When implementing slot planning material availability is vital, which may lead to putting pressure on suppliers to improve their OTD performance. The reality is, that from the perspective of WSZ's suppliers in China the factory is a minor player, because of low order volumes, which leads to the suppliers prioritising other orders over WSZ's orders. Since some of the suppliers WSZ uses are nominated by the product company, sanctioning theses suppliers is difficult, because the contract with them is managed by the product company. For suppliers nominated by WSZ there sometimes is a clause about sanctions for late delivery, but either they are not carried out or even if they are, they are not serious enough for the supplier to start improving its delivery.

The first risk management solution is to expand the supplier portfolio, so as to have a plan B especially for key material. Another obvious solution would be to be firmer about sanctioning late suppliers and change the clause on late delivery fees to have more economical impact. However, both may backfire. The supplier who already does not see WSZ as an important customer due to low volumes, may wish to stop collaboration altogether if it finds out that WSZ uses another supplier or tightens its OTD demands. This will lead to grave consequences for the supply of material for STCs. Thus, two solutions are suggested; one for the short term and another for the long term.

In the short term after information on real supplier OTD is available the suppliers who are systematically late should be given delivery dates earlier by the amount of days they are usually late. This way their bad OTD performance will not impact material availability and thus the start of assembly. Also, the root cause to their late delivery should be found out and if it is caused by e.g. WSZ initially placing the purchase order towards the supplier late, this should be fixed. Once the supplier starts to deliver on time the requested delivery date can be adjusted.

In the long term WSZ should consider consolidating suppliers as much as possible. This will both ease the sourcing team's task of supplier management and the volume of orders placed to one supplier will increase, automatically making WSZ a bigger player from the perspective of the supplier. However, consolidation should be carried out with appropriate risk management, so that disruptions in a supplier's processes will not lead to supply chain problems for WSZ.

These short and long-term solutions should be coupled with proper material demand forecasting towards suppliers. Firstly, it helps the supplier to adjust their capacity and plan production ahead. Secondly, it shows that WSZ will be placing orders also in the future and creates an impression of a customer that should be taken seriously.

To see the change KPIs will be followed. However, their validity should be evaluated. Firstly, they need to be defined so, that they show what is demanded from them. For example, as mention in Chapter 3.1.4, the in-house definition for production lead time also includes processes dependent on the product company's and customer's performance. This could be solved by changing the production lead time to end when production ends, which was done when calculating the "pure" production lead time. The current definition could be called SFTT or in-house lead time.

For information system related risks, it should be remembered that because SAP is a fairly new software at WSZ and there are many new employees, mistakes are made when inputting or downloading data. As shown by the example of supplier OTD measurement in Chapter 3.2.4 the meaning of a data set can be misunderstood, and the information taken out wrong.

When implementing slot planning and full-kitting, SAP knowledge may also cause obstacles. The scheduling done in slot planning is bound to differ from the scheduling given by SAP in leading to a need to change settings in SAP. Also, full-kitting may require changes in the routings of the sub-assemblies. With some consultation all SAP issues should be solvable and will only require some patience.

3.3 Improvement of production planning and control

3.3.1 Outline of practices for WSZ

The goal is to improve production planning and control practices at WSZ to be forward-looking and disciplined and be based on taking responsibility. An outline will be given separately for production planning practices and separately for production control practices. For production planning practices two dimensions will be discussed: the external with reference to product company order booking and material demand forecasting to the supplier, and the internal of ensuring production enablers. Here the main tool is slot planning supported by traffic lights. Production control again has the external aspect of communicating the status of an order to the product company and following the order moving through WSZ operations. The main tool is traffic lights supported by the task board in production with dates checked against slot planning scheduling.

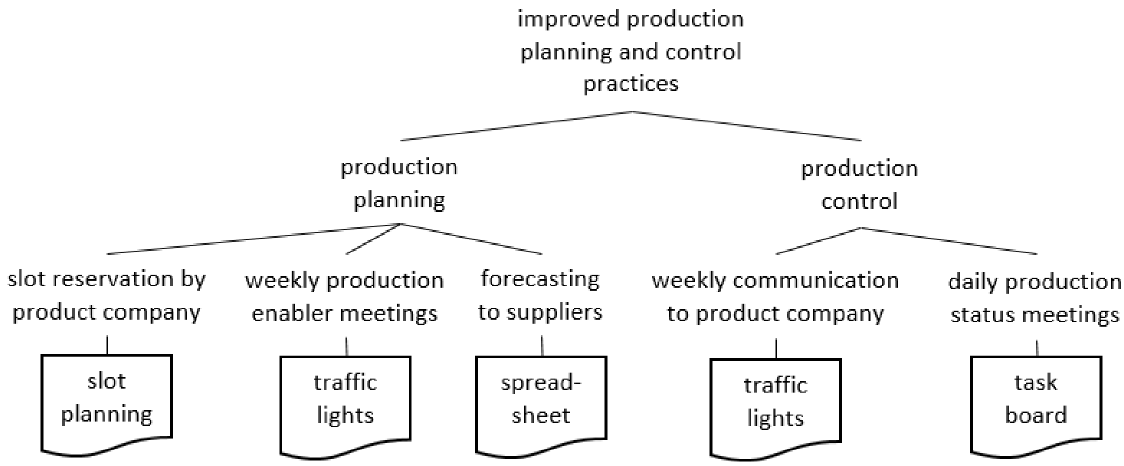


Figure 20. Outline of improved production planning and control practices for WSZ.

The trinity of taking responsibility, being forward-looking and disciplined is especially important when talking about planning. Product company order booking will happen through slot reservation and confirmation. Based on the current shop floor and assembly worker capacity there are five slots available weekly. One slot is two days of mechanical work. If mechanical worker capacity is increased shop floor capacity will become the constraint and the quantity of available slots will have to be recalculated. The number of slots by size of the product are as follows:

- Small and medium – 1 slot
- RTC and small or medium with ejector – 2 slots
- Large – 3 slots

The slot reservation process is shown in Appendix 11. Slot reservation can be done as far ahead as wanted, but with a purchasing lead time of 2-3 months slots need to be confirmed at least 3-4 months before the requested available for delivery date. When the product company reserves and then confirms a slot WSZ informs the following dates: when the product company must send the PO with the EBOM, the freezing point after which no changes can be made to the order for material purchasing to be carried out without disturbances, the estimated FAT date if it is required by the end customer and the date the product will be on the ship or the bonded warehouse. If the product company does not deliver the EBOM is agreed or changes are made to the order after the freezing point the slot is lost and production is rescheduled to the next available slot. Conversely, if WSZ delivers late, it carries the cost. For WSZ to deliver, it is essential that all the production enablers are in place, which brings us to the in-house production planning practices.

The assumption is, that with full-kitting the product will flow through production making the main task of production planning to have everything in place to start production per agreed slot. For this weekly production enabler meetings will be held where the orders with production starting in the upcoming 8 weeks will be discussed. These meetings will be led by the order management manager or planner with input from employees of all departments handling STC orders, meaning engineering, purchasing, production and quality. Looking at the upcoming 8 weeks answers the forward-looking dimension and holding the meetings at a weekly basis requires discipline. However, to sustain these two the meeting leader needs to be committed to what he or she does and embrace the leadership role, as discussed in Chapter 2.5.1.

For production planning it is suggested to use the traffic lights tool, shown in Appendix 12. When booking a slot, the product company is promised a delivery time which includes a buffer the length of time the product spends in assembly. The goal of the production enabler meetings is to ensure that the product will really be ready by the promised delivery date and in situations where there is a risk that the buffer will be eaten up, to take action and still ensure on-time delivery. This answers to the long-term goal for WSZ of having 100% OTD performance.

Since from all the production enabler WSZ has most problems with material availability, it is essential, especially for long lead time materials, that the order management manager forecast orders at least 12 months ahead and share the forecast with the purchasing team at a quarterly basis. This enables the purchaser to forecast towards the supplier, and the supplier to plan his production accordingly.

For production control the basics are already in place. To communicate the status of sales orders there are weekly meetings with the product company. However, emphasis should now be placed on sharing the real situation, also when there are issues that may lead to late delivery. As Jacobs et al. (2011, p. 62) say, customers prefer honest answers, even if they are unpleasant, to inaccurate information. When communicating with the product company employees of WSZ are responsible for sharing accurate information. This should be easier through the weekly production enabler meetings.

For in-house production control there are already daily “planning” meetings where the status of the products on the shop floor are discussed. These need to be renamed into “production status” meetings, since that is their content. It is suggested the meetings to be moved to the production area.

3.3.2 First intervention – full-kitting

The goal of full-kitting is to enable a synchronous manufacturing with products flowing through production and production lead times being as planned. This is made possible by having all the material needed in production available, without the need to stop assembly due to material shortages. Full-kitting should lead, firstly, to a lower quantity of WIP and, secondly, predictable dates for the finish of assembly. Umble & Srikanth (1990, p.109) compare the material flow in a manufacturing environment to a river. The deeper the river is, that is the more inventory there is, the less visible the submerged obstacles, like variable processing time, bottlenecks or inadequate information, are (Umble & Srikanth 1990,

p. 110). Thus, by lowering the level of the river, analogously WIP, identifying underlying issues becomes easier.

Before starting full-kitting the layout of the STC assembly area was changed to have predefined stations. Racks were placed at each station, where the material was moved to from the warehouse for the start of assembly. The new layout is shown in Appendix 13. A task board was set up to manage and follow the status of upcoming products and those already in assembly. The task board is shown in Appendix 14.

For full-kitting to work a process chart was constructed, for all the parties responsible to be aware of their role and sequence of actions. The process chart is shown in Appendix 15. Before full-kitting all orders one order was run through the process to see what needed improvement. After this full-kit was implemented into all STC sales orders. Weekly meetings were held to discuss and solve any issues that arose. Points raised are given in Appendix 16. Data was collected on the amount of WIP and to compare to the data in Chapter 3.1.4.

3.3.3 Second intervention – managing material availability

The major hindrance to the success of the first intervention was not having the needed material for kitting, so managing material availability was carried out as a second intervention. The goal of managing material availability is to have all the material available by the planned start of assembly date. For this a buyer board, shown in Appendix 17, was put up. The buyer board had similar task cards as the production task board and the cards were also put up by the planner.

Material following was started 13 workdays before start of painting, that is 7 workdays before kitting. For each product the material availability of the sub-assemblies was checked first based on supplier promised delivery dates and after kitting based on physical material availability. The scheduling logic is shown in Figure 21. Suppliers are told to deliver 8 days before start of assembly, which includes three workdays for warehouse to kit the order and five days leverage for the suppliers to deliver the material. The latter period includes warehouse receival and IQC for arriving material. In other words, if suppliers deliver on time, the material should be available for kitting six workdays before start of assembly.

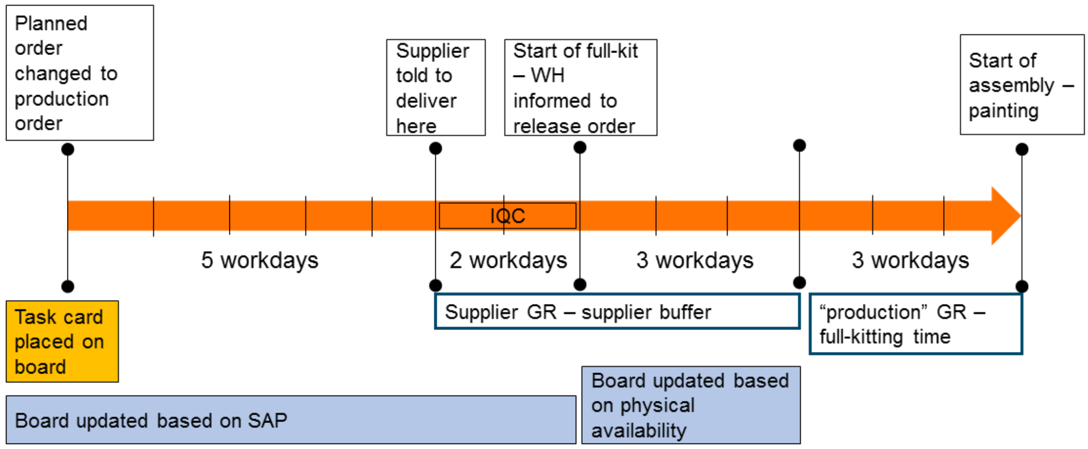


Figure 21. Scheduling of material availability following.

A process chart, shown in Appendix 18, was created, for all the parties responsible to be aware of their role and the sequence of actions. The buyer board was tested with two orders. Buyers purchase based on materials and do not know to which sales order each material belongs unless they check it separately. Therefore, the buyer involved in the buyer board testing was asked to also follow hours spent on the process.

3.3.4 Visual management tools

The tools suggested to use can be divided into existing and new tools. The traffic lights tool is a spreadsheet already in use in other product lines. The task board and buyer board are new tools. Emphasis is placed on using the tools for visual management purposes. For cognitively effective information conveyance objectives visual management is a good close-range communication strategy (Tezel, Koskela & Tzortzopoulos 2016).

The traffic lights tool should be made available for STC order management and used when communicating the status of product to the product company. The traffic lights tool has columns indicating all the steps from offer review to invoicing of a product with clearly marked responsible people for each step. The status of the step is marked with green, yellow and red to indicate completion, in process and issues, respectively. This makes it easy to see at which step the product currently is and communicate any issues that may have arisen. Each row represents one product. The tool is shown in Appendix 12.

The task board for production management and the buyer board for material availability management are new tools. The task board is a big board standing in the production area with a column for each station on the STC production area. Horizontal columns indicate steps from kitting to assembly. Each tank product is represented by a card placed on the board by the planner. The aim of the task board is to visualise pull production. When a square above the task card is available it means there is available capacity at the next step and the card, hence the product, can be moved to the next step. The planner marks a queue number on the task card to prioritise the order in which products are moved. Prioritisation happens based on ODD. A photo of the task board and task card is shown in Appendix 14.

The buyer board is a white board placed into the office area showing the material availability by product. At the top of each column the planner places a buyer task card. The column is divided into the sub-assemblies shown in Appendix 5 and the buyer marks with magnets the availability of materials for each sub-assembly. A green magnet indicates that the materials are available, a yellow magnet that the materials are on their way and should be available according to schedule and a red magnet, that there will be issues with one or more materials of the particular sub-assembly. A photo of the buyer board and buyer task card is shown in Appendix 17.

Visual management carries multiple functions. It brings process transparency, so information held in people's minds or private spreadsheets is available to everyone. This also facilitates job performance since there is no need to remember everything. Having everything presented visually promotes management by facts, because there is a limited amount of ways something predefined can be interpreted. Having everything visually transparent promotes discipline through group pressure to take responsibility and properly maintain correct procedures. (Tezel, Koskela & Tzortzopoulos 2016) Discipline and taking responsibility are two of the three characteristics for improved production planning and control practices at WSZ. The last point raised is also of consequence in the context of China, where not "losing face" in the sense of avoiding situations where one can end up being humiliated in front of others (Hofstede, Hofstede & Minkov 2010, p. 110) is important.

4. RESULTS AND CONCLUSION

4.1 Results

4.1.1 Main results

The objective of the study was to improve production planning and control practices at WSZ, so they answer to current and future needs. The main result is an outline of practices that need to be implemented for production planning and control to become based on taking responsibility, forward-looking and disciplined. As a starting point for the implementations two interventions were carried out. The detailed results from the interventions are given in the following chapters. The overall results of studying the processes at WSZ are:

- Material availability is a major issue, which can be solved with forward-looking disciplined material availability management.
- Not being properly informed on details related to own responsibilities leading to inaccuracy in communication.
- The major challenge for implementing new practices is lack of discipline.

The most common thing that came up in unstructured interviews as the reason for bad OTD was having material shortages in production. However, with proper material availability management and root cause analysis as to the reason of material being unavailable it should be possible to fix most material availability issues. Related to this it was noticed that there were multiple situations when an employee was asked for details related to his or her area of responsibility which he or she was unable to answer. Though it is obvious one cannot remember everything, if this happens continuously it leads to doubting the professionalism of that person. This also raises questions as to the accuracy of the overall information communicated both inside WSZ and to WSZ's stakeholders, especially suppliers and customers.

Being uninformed on the details of one's responsibilities is a form of being undisciplined in personal follow-up tasks. This lack of discipline is also seen as the major challenge for implementing and, especially, sustaining new practices. This was particularly prominent when decisions on rules of working made together were not carried through or dropped shortly after implementation. Peter Drucker's famous quote "culture eats strategy for breakfast" is quite applicable to WSZ.

4.1.2 Results from full-kitting

The main lessons learnt through full-kitting were:

- Material availability is a major issue.
- New ways of working are not sustained unless there is someone overlooking their following.
- Lack of root cause analysis for material shortage reasons.

During the 14 weeks data was collected on full-kitting out of the 23 orders released six were really full-kitted and 16, including all the full-kitted, finished. However, only 7 products were delivered, because the product company had not delivered shipping instructions. Products released to production with shortage were missing a pump, control panel, blower, valves, nameplates or a flange. Pumps are assembled in-house and all their material was available as planned. Upon inspection it was found out a batch of pump heads needed for pump assembly was rusted, which affected pump availability for multiple STCs. The control panel is also assembled in-house. It being unavailable means its assembly was not started early enough to be made available for the start of STC assembly.

Products with shortage were released into production with the logic that while the tank is in painting and drying the missing material would arrive. However, as will be seen in Chapter 4.1.3, this only lead to blocking the start of assembly of products that did have all the material available. Multiple products were found to be waiting for different material, though in some cases the products could have been prioritised and the missing component borrowed from the another waiting product, so that at least one would get ready. It was also noticed that often the planner was not informed about the material availability in general or when some missing component would be available.

Data was collected on the timeliness of painting, start of assembly and finishing. This is shown in Figure 22. Each column represents one of the finished products and the y-axis shows how many days late painting, start of assembly or finish of assembly was.

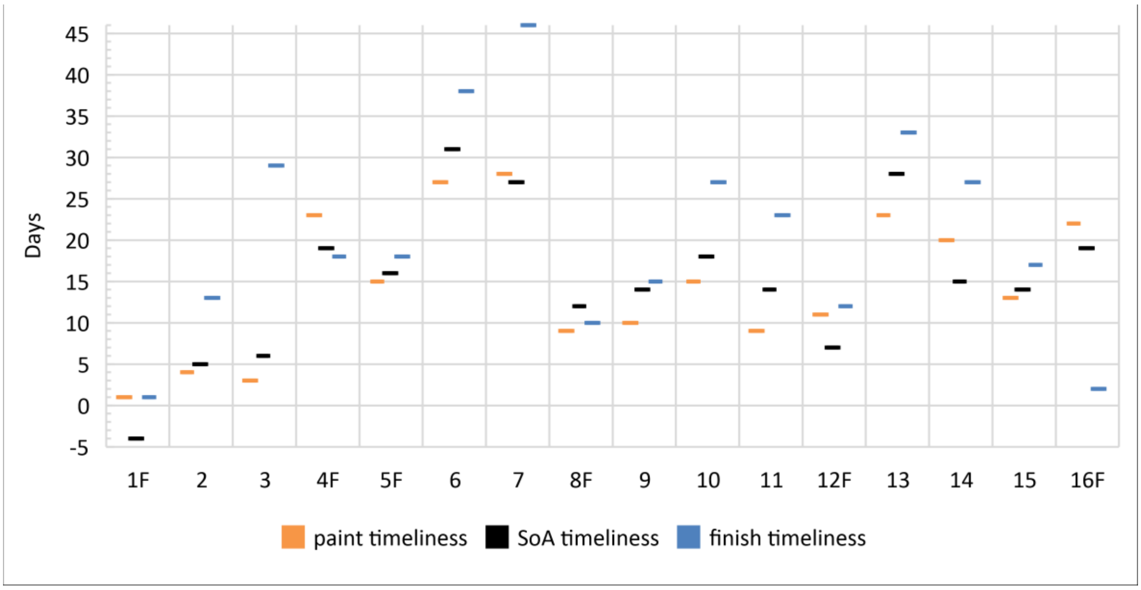


Figure 22. Paint, start of assembly and finish timeliness of products started and finished during full-kitting. Those really full-kitted are marked with an “F” after the number.

Only the first product was assembled earlier than planned. In most cases painting and SoA are roughly as late, on average 17 and 18 days, respectively, whereas the product is finished on average 21 days later than planned. In part this can be explained by the fact, that products stand waiting for material when already released into production. The full-kitted orders marked with an “F” in Figure 22 are the only ones where finishing assembly lateness is less than SoA lateness. Otherwise, considering the sample size, nothing conclusive can be said about the full-kitted products.

Data on the amount of WIP was collected and is shown in Figure 23. The low levels of WIP during the first 7 weeks can are explained by a lower than usual quantity of orders. The batch of rusted pump heads was discovered on the week starting 17th of September after which the amount of WIP steadily increased as partly assembled products where left waiting and new products released into production. 1st of October started a week-long national holiday, which had no effect on the STC worker capacity, since new products were released into production on that week too.

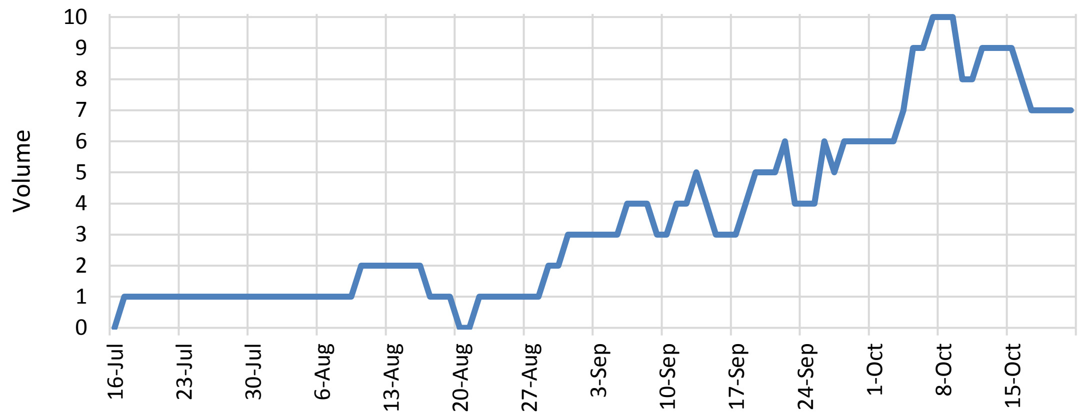


Figure 23. WIP levels during 14 weeks of full-kitting.

Results from the full-kitting intervention were compared to the results of the data analysis carried out in Chapter 3.1.4. Of the products delivered one was delivered early and six were delivered late. The "pure" production lead time from order release to actual finish was studied. The planned and actual values for each product are shown in Figure 24. Full-kitted products showed a better production lead time performance than not full-kitted products, except the product marked "16F", which was accidentally released too early.

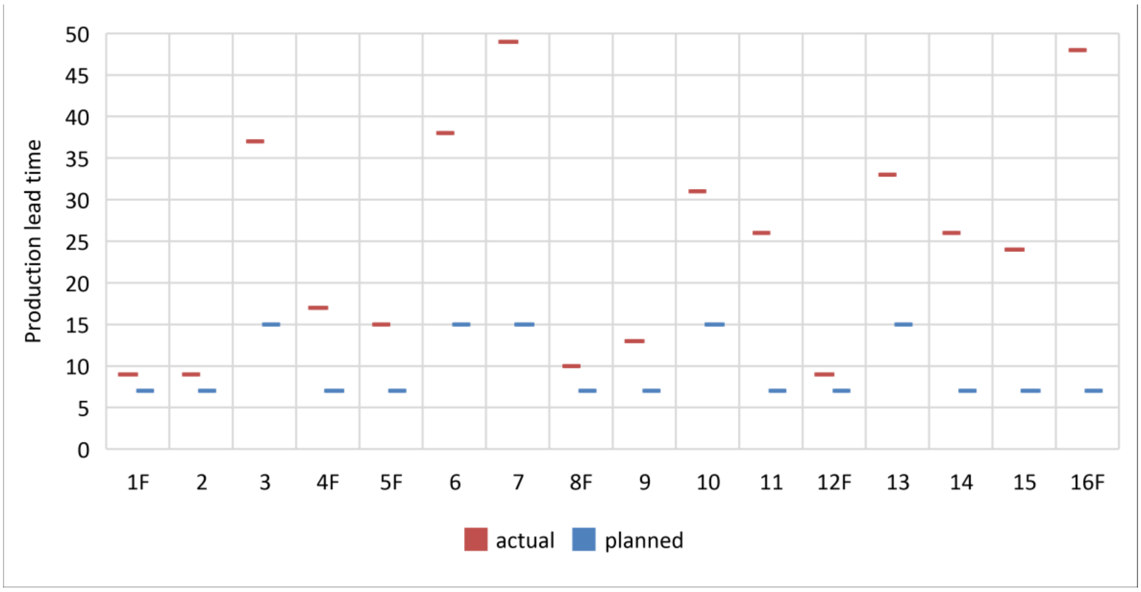


Figure 24. Actual and planned "pure" production lead times of full-kitted orders. Those really full-kitted are marked with an "F" after the number.

Overall, it can be said that when products were full-kitted they flowed through production. However, with issues in material availability production was both started and finished late, which is why material availability management is a top priority for successful full-kitting.

4.1.3 Results from managing material availability

The main lessons learnt through following material availability were:

- Through systematic action it is possible to have all material available for start of assembly.
- Even with all material available on-time start of assembly is not possible if there is no space on the shop floor or assembly worker capacity.
- The proposed way of following material availability puts pressure on buyer resource capacity.

Material availability following on the buyer board was tested for two sales orders each with one product. For both products all the material except the pump was available as planned. The pump is assembled in-house and all the needed for pump assembly was available, however, upon inspection it was discovered that the pump heads were rusted, and new ones had to be ordered. Tank painting was carried out while waiting for the new batch of pump heads to arrive. Tank assembly was started late, because there was not enough assembly worker capacity. This shows that material availability is the major issue and bottleneck to flowing production. Once it is fixed the bottleneck moves into production.

Information on time the buyer used to check material availability and update the board was recorded. For each order she spent 2 hours for the initial check and another 30 minutes for updates. If we assume that monthly production levels are the same as in the period analysed in Chapter 3.1.4, going through the whole buyer board process would amount to 4-5 full workdays in a 20-workday month. This time does not include the time used to place the purchase orders for the material followed in the buyer process. In the long run this is not sustainable, since the buyer is responsible for placing purchase orders for other product lines' materials too and does not have the time to invest into following the availability of all the materials needed for each STC product.

4.2 Reliability and validity

The reliability and validity appraisal can be applied to the numerical data analysed when discussing the current state in Chapter 3.1.4 and the results from full-kitting in Chapter 4.1.2, and to the main results given in Chapter 4.1.1. Most numerical data was taken from SAP, but the reality is that not everything marked into SAP is accurate, which raises doubts as to its reliability. Sometimes data is not updated, sometimes data is updated later than it should be, and sometimes correct data is marked into the wrong place turning it into wrong data. An example of the first case is the way WSZ does not follow the actual start of assembly as mentioned in Chapter 3.1.4.

An example of updating data later than it should be is the way the actual assembly finishing date is marked into SAP. Based on the procedure it should be marked directly after assembly has been finished. However, this does not always happen, which means that the results for finishing timeliness and "pure" production lead time given in Chapter 3.1.4 may show worse performance than it really is.

An example of marking data into the wrong place is the way delivery dates are marked into SAP. The product company marks the FOB date in the PO it sends to WSZ. Depending on the agreement with the customer the FOB date is the day the ready product should be on the ship or at a pre-defined warehouse for customer pick-up. WSZ manually calculates back two weeks to get the date when the ready product should be available for delivery. The inaccuracy in SAP comes from sometimes the FOB date and sometimes the available for delivery date being marked as the "SAP date". This "SAP date" was used to analyse the OTD performance of WSZ in Chapters 3.1.4 and 4.1.2. Since it is unknown which date was actually marked into SAP for each sales order it may be that the OTD performance for some is better than shown in this thesis.

No statistically valid conclusions can be given on the results for full-kitting in Chapter 4.1.2 due to the small sample size. However, investing time and effort into full-kitting implementation brought significant learning, which can be applied to other product lines where full-kitting will be extended. Thus, the output of the interventions should be considered from a qualitative perspective, in which case valid conclusions have been attained.

4.3 Achievement of objective and contribution to existing knowledge

This thesis set out to answer "*How to organise production planning and control at WSZ so that is it responsive to the needs of a multi-product factory?*" with the objective to improve production and planning practices at WSZ, so they answer to current and future needs. For this purpose the future a sketch of the future state was given, where the production planning and control practices should be based on taking responsibility, being forward-looking and disciplined. Suggested practices were outlined and two interventions carried out to support the implementation of the suggested practices.

Though the numerical results of the interventions cannot be considered good, the objective of giving an outline of improved production planning and control practices which are realistic to implement was achieved. Additionally, through the interventions it was found out what challenges will be encountered when implementing new practices.

The long-term goal of WSZ is to have 100% OTD performance. The STC product line is still very far from this goal. Employees see that the major reason behind the current situation are material shortages in production. However, this study and especially the material availability management intervention showed that the core reason lies in the lack of systematic and forward-looking practices concerning production planning and control. Actions to fix issues are carried out when it is already too late, and risks are not considered in advance. In addition, when improvements are made, they are not sustained unless there is someone constantly pushing for follow-up.

While carrying out research current ways of working and reasons behind certain actions were questioned. This lead to findings related to e.g. differences between planning and production when dividing STCs by size, supplier delivery data updating, root cause of nameplate shortages and scheduling. Through benchmarking to DCT and DCV new ways for production planning and control were uncovered. Emphasis was placed on communication inside WSZ and from WSZ to the product company. This lead to wider information sharing between departments and better understanding the needs of the product company.

The information gathered for the research would have been available to everyone working in WSZ, meaning anyone could have put in the time and participated in improving processes. However, as is usual, with each person having his or her daily routines and additional last-minute tasks, not all the analysis needed is carried out. From such a perspective it can be said with assurance that this research contributed to existing knowledge.

4.4 Recommendations for the future

4.4.1 Recommendations for the STC product line

For the STC product line the next steps are:

1. Follow through with the outline of practices described in Chapter 3.3.1.
2. Continue with full-kitting the sales orders.
3. Manage material availability proactively.

It is suggested slot planning be introduced in more detail to the delivery management teams placing the sales orders. The orders are placed by people located in Poole, the UK and in Shanghai, China, with the latter sharing sales order information with the former. However, this does not always happen, so the need to communicate between themselves will be emphasised.

To manage material availability and other factors of production proactively weekly production enabler meetings will be booked and held. The order management manager who does order forecasting will be asked to schedule and send the materials manager material demand forecasts at a quarterly basis. For production control the already set weekly meetings with the product company will be continued, but it is up to the person in touch to carry through delivering the “ugly truths” and take responsibility for the accuracy of the information shared. The daily “planning” meetings should be renamed into “production status" meetings and moving them to the production area or placing a visual board for following should be discussed with the parties concerned.

Concerning the interventions, full-kitting should be continued. Even though full-kitting was not fully followed through during the first intervention, it was clear that by full-kitting the issues related to material availability were moved upstream in the supply chain. Having problems arise closer to the start point gives more time and leverage to fix them. It also makes later steps more predictable which is essential for slot planning to work. For orders to really be full-kitted discipline is vital.

Material availability should be continued to follow, but in a manner that is sustainable and does not tie up as much buyer capacity as the buyer board in its current form. It is suggested to follow 3-5 long lead time items or key components. To this can be added following 2-3 components that tend to be late. Root cause analysis should be carried out to find out the reason for lateness of these components. Continuing using the white board is suggested for visual purposes.

4.4.2 Overall recommendations

The overall recommendations are:

- Extend the outlined production planning and control practices to other product lines.
- Emphasise time-based thinking as suggested by QRM in Chapter 2.2.
- Sustain and improve implementations.

It is suggested the new practices outlined in Chapter 3.3.1. should be extended into other product lines starting with BWMS. Because sales orders for BWMS come from the same product company as for STCs communicating new ways of working towards the product company interface should be easy. The extension will require full-kitting BWMS orders and managing their material availability. BWMS are more complex as products, so it is good that the full-kitting process has already been tested on a straightforward product.

Emphasising time-based thinking refers to not only production lead time and SFTT but also office tasks and purchasing lead times. WSZ has received multiple complaints that it sends order acknowledgements (OA) to product companies too slowly. In cases when sourcing for new materials has to be carried out before acknowledging the order long order acknowledgement times are unavoidable. However, this cannot be used as an excuse for sales orders with already sourced material.

Also, the possibility for shorter purchase lead times should be studied. For example, as was discussed in Chapter 3.2.4 for STCs the long lead time item is the tank and for some STC sizes also the pump and blower. With the change of the tank supplier it may be possible to negotiate the purchasing lead time down to one month. If this happens the next long lead time item will be the one defining the overall lead time of the product. As shown in Appendix 2, the shorter the lead times the more accurate planning can be.

The most important recommendation is to sustain and improve implementations. Results can only be seen through systematic doing. Yet, some suggestion for practice seemingly reasonable at the time of writing may lose its purpose or value in the future. Therefore, the outlines given in this thesis should not be followed blindly, but with consideration to what additional value they bring and what purpose they serve. If they lose their validity further improvements should be carried out always keeping the final goal, 100% OTD performance, in mind.

REFERENCES

Buxey, G. 2003. Strategy not tactics drives aggregate planning. International Journal of Production Economics, vol. 85(3), pp. 331-346.

Candi, M. 2017. How to use design thinking to change cultures. Available online (accessed 4th of November 2018): https://medium.com/thingsflux/how-to-use-design-thinking-to-change-cultures-9383e6c1c222.

Dettmer, H.W. 1998. Breaking the constraints to world-class performance. ASQ Quality Press, Milwaukee. 288 p.

Emboava, F.N., Cardoso, R. & Tammela, I. 2017. A comparative analysis between the quick response manufacturing and time-based competition methodologies. Brazilian Journal of Operations & Production Management, vol. 14, pp. 414-427.

Fernandes, N.O. & Carmo-Silva, S. 2011. Workload control under continuous order release. International Journal of Production Economics, vol. 131, pp. 257-262.

Goldratt, E.M. 1994. It's not luck. USA: The North River Press Publishing Corporation. 283 p.

Goldratt, E.M. 1997. The critical chain. USA: The North River Press Publishing Corporation. 246 p.

Goldratt, E.M. 2014. The goal: a process of ongoing improvement. 4. edition. USA: The North River Press Publishing Corporation. 362 p.

Groysberg, B., Lee, J., Price, J. & Cheng, J.Y-J. 2018. Changing your organisation's culture can improve its performance. Here's how to do that. Harvard Business Review. January-February 2018.

Hinckeldeyn, J., Dekkers, R., Altfeld, N. & Kreutzfeldt, J. 2010. Bottleneck-based synchronization of engineering and manufacturing. International Association of Management of Technology. IAMOT 2010 proceedings.

Hofstede, G., Hofstede, G.J. & Minkov M. 2010. Cultures and organisations, software of the mind, intercultural cooperation and its importance for survival. McGraw Hill eBook. 561 p.

Holmström, J., Ketokivi, M. & Hameri, A. 2009. Bridging practice and theory: a design science approach. Decision Sciences Institute, vol. 40(1), pp. 65-87.

Hopp, W.J. & Spearman, M.L. 2004. To pull or not to pull: What is the question? Manufacturing & Service Operations Management, vol. 6(2), pp. 133-148.

Incoterms rules. 2018. Incoterms® rules 2010. Available online (accessed 30.9.2018): https://iccwbo.org/resources-for-business/incoterms-rules/incoterms-rules-2010/.

Jacobs, F.R., Berry, W.L., Whybark D.C. & Vollmann, T.E. 2011. Manufacturing planning and control for supply chain management. E-book: McGraw Hill Companies, Inc. 544 p.

Kern, S.K.M. 2018. Improving the on-time delivery performance in a multi-product make-to-order environment. Aalborg University. 141 p.

Lawrence, P.R. 1969. How to deal with resistance to change. Harvard Business Review. Available online (accessed 25th of October 2018): https://hbr.org/1969/01/how-to-deal-with-resistance-to-change.

Little, J.D.C. & Graves, S.C. 2008. Building intuition: Insights from basic operations management models and principles by editors Chhajed, D. & Lowe, T.J., pp. 81-100.

Merriam-Webster. 2018. Word search: practice. Available online (accessed 9th of September 2018): https://www.merriam-webster.com/dictionary/practices.

Northouse, P.G. 2007. Leadership theory and practice. USA: Sage Publications, Inc. 4th edition. 395 p.

Olhager, J., Rudberg, M. & Wikner, J. 2001. Long-term capacity management: Linking the perspectives from manufacturing strategy and sales and operations planning. International Journal of Production Economics, vol. 69(2), pp. 215-225.

Pan, L. & Kleiner, B.H. 1995. Aggregate planning today. Work Study, vol. 44(3), pp. 4-7.

Saunders, M., Lewis, P. & Thornhill, A. 2009. Research methods for business students, 5th ed. Prentice Hall, Harlow. 614 p.

Schmenner, R.W. 1988. The merit of making things fast. Sloan Management Review, vol. 30 (1), pp. 11-17.

Singhal, J. & Singhal, K. 2007. Holt, Modigliani, Muth, and Simon's work and its role in the renaissance and evolution of operations management. Journal of Operations Management, vol. 25(2), pp. 300-309.

Stevenson, M., Hendry, L.C. & Kingsman, B.G. 2005. A review of production planning and control: the applicability of key concepts to the make-to-order industry. International Journal of Production Economics, vol. 43(5), pp. 869-898.

Stevenson, M., Huang, Y., Hendry, L.C. & Soepenberg, E. 2011. International Journal of Production Economics, vol. 131, pp. 689-700.

Stevenson, W.J. 2015. Operations management. United States of America: McGraw Hill Education. 12th edition. 904 p.

Suri, R. 2010a. Going beyond lean. Industrial Engineer, April, pp. 30-35.

Suri, R. 2010b. It's about time. The competitive advantage of quick response manufacturing. Taylor and Francis group, LLC. 210 p.

Suri, R. 2015. A timely metric. Industrial Engineer, October, pp. 36-41.

Tezel, B.A., Koskela, L.J. & Tzortzopoulos, P. 2016. Visual management in production management: a literature synthesis. Journal of Manufacturing Technology Management, vol. 27(6), pp 766-799.

Thürer, M., Land, M.J. & Stevenson, M. 2016. Card-based workload control for job shops: Improving COBACABANA. International Journal of Production Economics, vol. 147, pp. 180-188.

Thürer, M., Land, M.J., Stevenson, M. & Fredendall, L.D. 2016. Card-based delivery date promising in high-variety manufacturing with order release control. International Journal of Production Economics, vol. 172, pp. 19-30.

Thürer, M., Stevenson, M. & Land, M.J. 2016. On the integration of input and output control: workload control order release. International Journal of Production Economics, vol. 174, pp. 43-53.

Thürer, M., Stevenson, M. & Protzman, C.W. 2015. COBACABANA (Control of Balance by Card Based Navigation): An alternative to kanban in the pure flow shop? International Journal of Production Economics, vol. 166, pp. 143-151.

Thürer, M., Stevenson, M., Silva, C. & Qu, T. 2017. Drum-buffer-rope and workload control in high-variety flow and job shops with bottlenecks: an assessment by simulation. International Journal of Production Economics, vol. 188, pp. 116-127.

Thürer, M., Stevenson, M., Silva, C., Land, M.J., Fredendall, L.D. & Melnyk, S.A. 2014. Lean control for make-to-order companies: integrating customer enquiry management and order release. Production and Operations Management, vol. 23(3), pp. 463-476.

Umble, M.M. & Srikanth, M.L. 1990. Synchronous manufacturing, principles of world class excellence. South-Western publishing co., Cincinnati. 270 p.

Wärtsilä annual report. 2017. Available online (accessed 18th of September 2018): http://www.wartsilareports.com/en-US/2017/ar/download-center/build-your-pdf/.

Wärtsilä Hamworthy. 2018. Hamworthy plc acquisition. Available online (accessed 18th of September 2018): https://www.wartsila.com/hamworthy.

Wärtsilä. 2018. People management. Available online (accessed 25th of October 2018): https://www.wartsila.com/sustainability/sustainability-management/personnel.

INTERVIEWS

Bian, E., purchasing manager at WSZ. Multiple interviews between July and October 2018.

Furlani, PP., planner for order intake and planning at DCT. Interview 21.8.2018.

Honkala, M., general manager in delivery management at DCV. Interview 1.10.2018.

Ji, M., engineering manager at WSZ. Multiple interviews between July and September 2018.

Lagerström, T., general manager at WSZ. Multiple interviews between July and August 2018.

Lehikoinen, K., operational excellence manager for supplier integration and cost control at DCV. Interview 11.10.2018

Leppiniemi, J., purchasing manager at DCV. Interview 9.10.2018.

Nuotio, T., production operational excellence manager at DCV. Interview 1.10.2018.

Shen, B., order management manager at WSZ. Interview 27.6.2018.

Shi, J., SAP development manager at WSZ. Multiple interviews between July and September 2018.

Sun, A., customer care supervisor at WSZ. Interview 1.8.2018.

Wang, O., quality manager at WSZ. Interview 2.7.2018.

Xu, J., order and materials management manager at WSZ. Multiple interviews between July and October 2018.

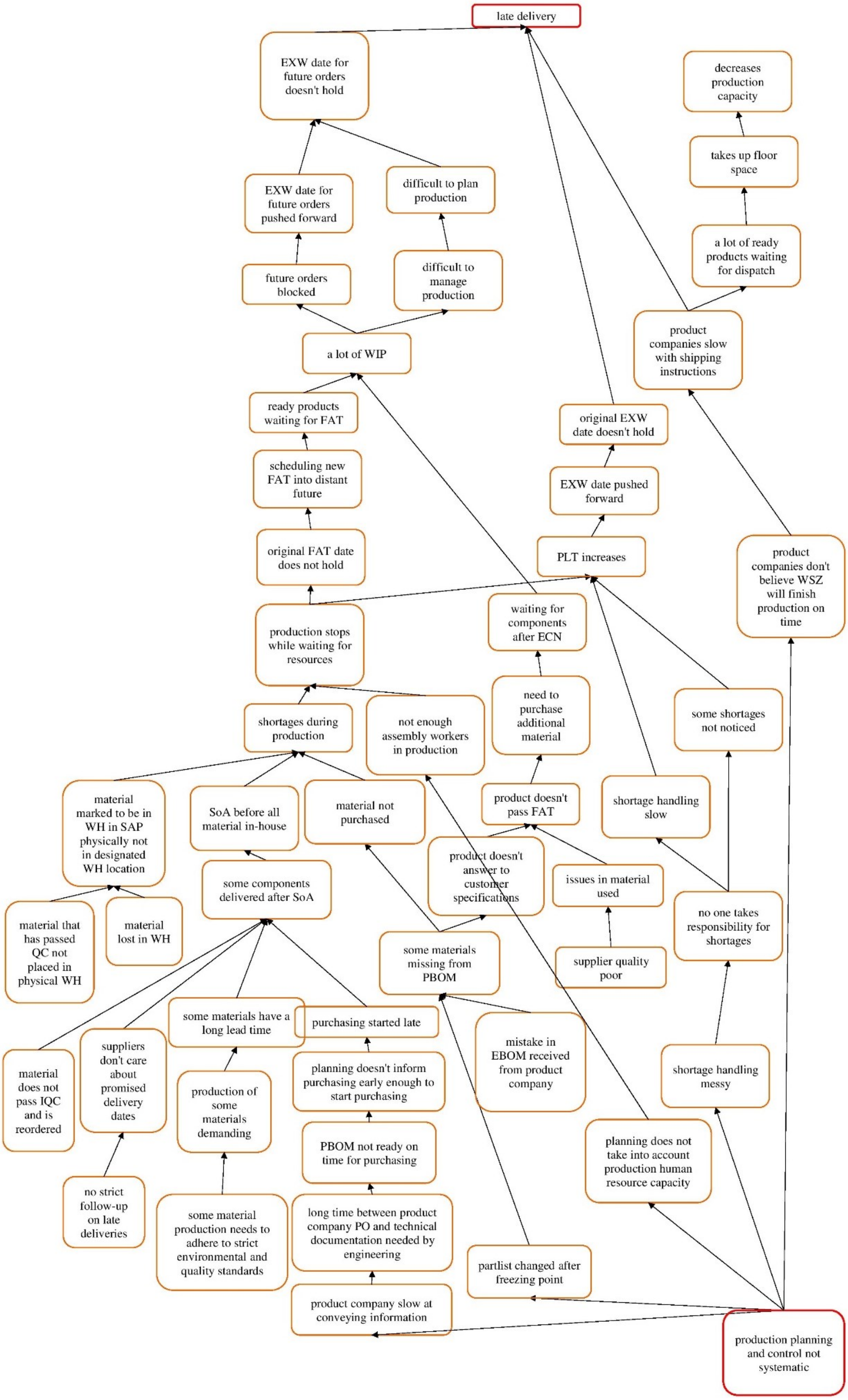
Ylikantola, T., general manager, delivery at Poole, the UK, internal customer of WSZ. Multiple interviews during October 2018.

Ylipulli, J., senior development manager at DCV. Multiple interviews between July and October 2018.

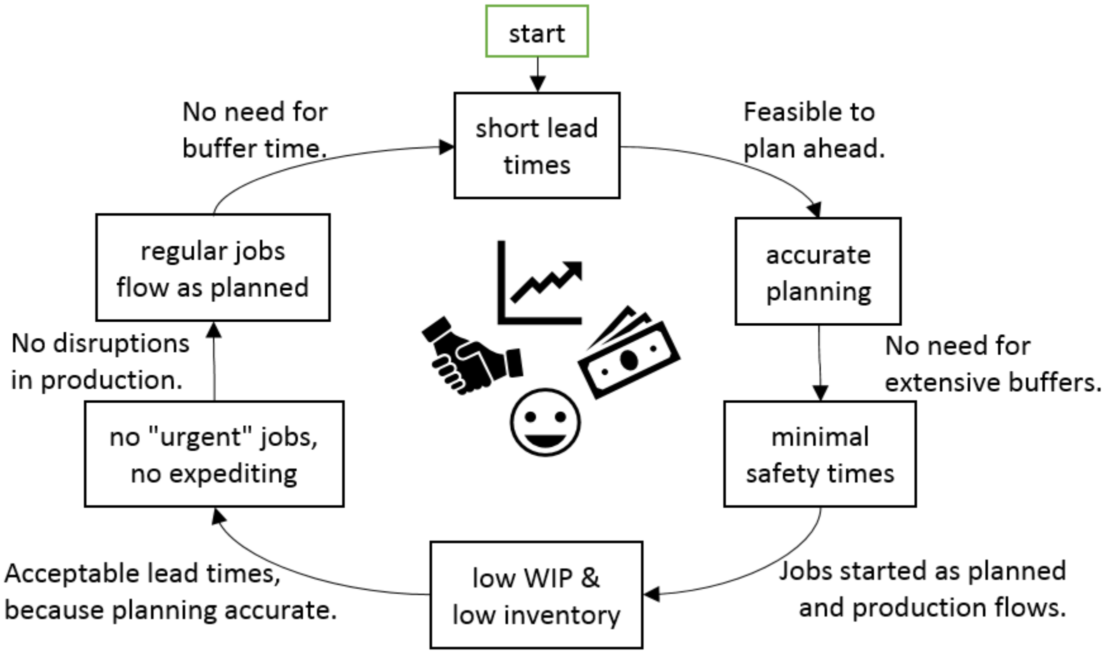
Zhu, C., mechanical production supervisor at WSZ. Multiple interviews between July and October 2018.

APPENDIX

APPENDIX 1. CURRENT REALITY TREE



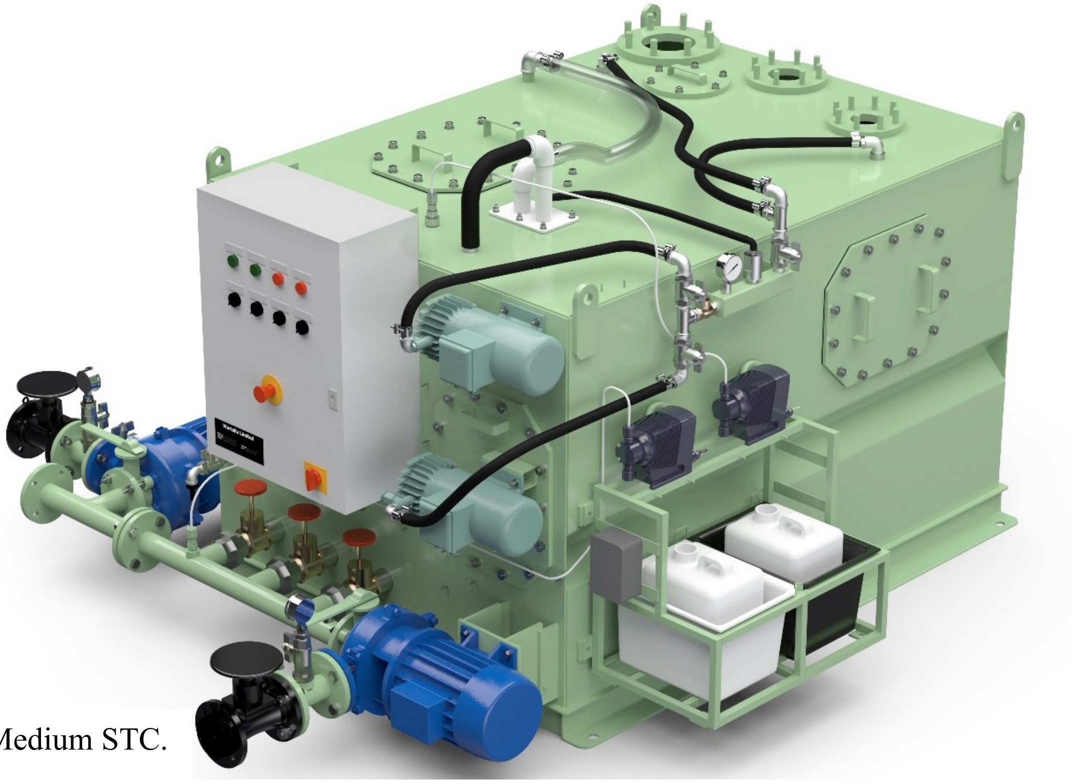
APPENDIX 2. POSITIVE RESPONSE TIME SPIRAL



A positive response time spiral as an answer to the response time spiral shown in Figure 8. The logic behind it is that the same way as long lead times lead to even longer lead times short lead times can lead to even shorter lead times as buffers and waiting are cleared out.

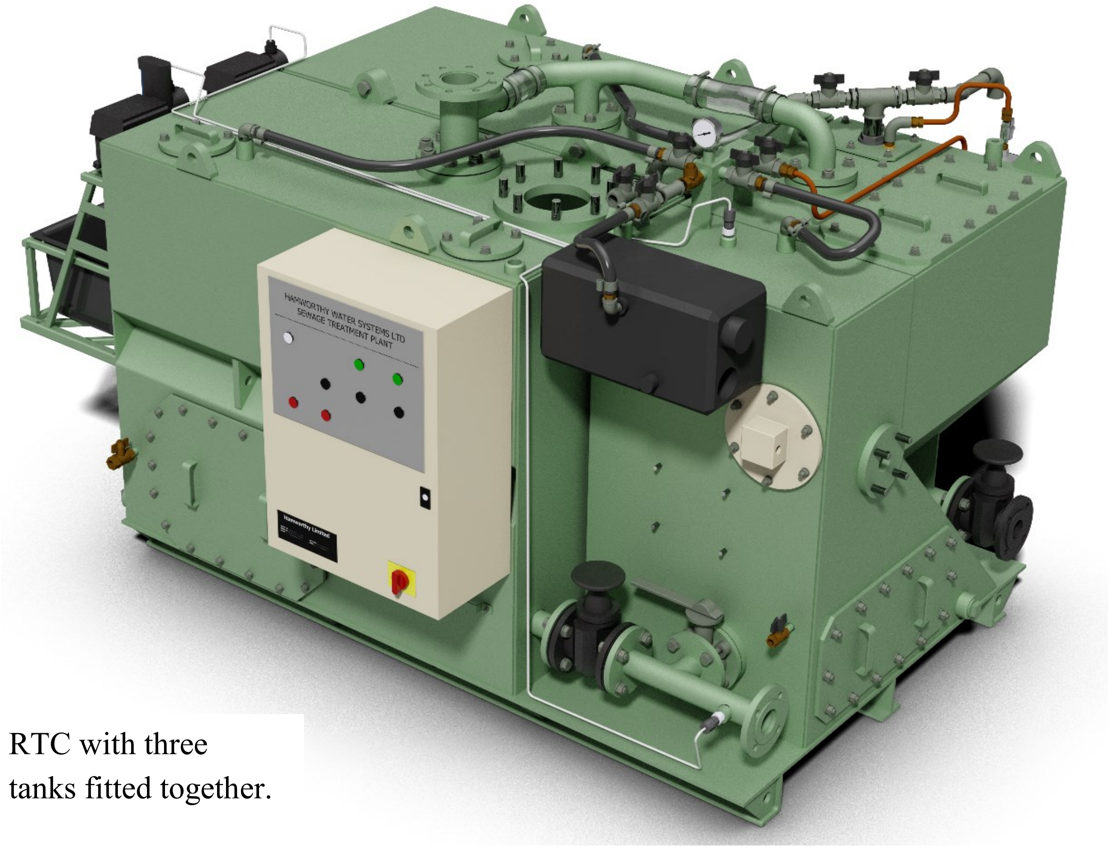
Arguably, the most difficult thing is the start since it requires cutting lead times in the first place. This requires first and foremost discipline: discipline in prioritising tasks, discipline in not putting off tasks and being systematically on top of one’s work. Applying this to WSZ and the STC order processing process this means actions like sending the product company the OA within 3 workdays of PBOM readiness, monitoring material arrival so as to be ready to start production as soon as all the material has arrived and asking for shipping instructions before production is finished, not after.

APPENDIX 3. PHOTOS OF STC TYPES FOR REFERENCE

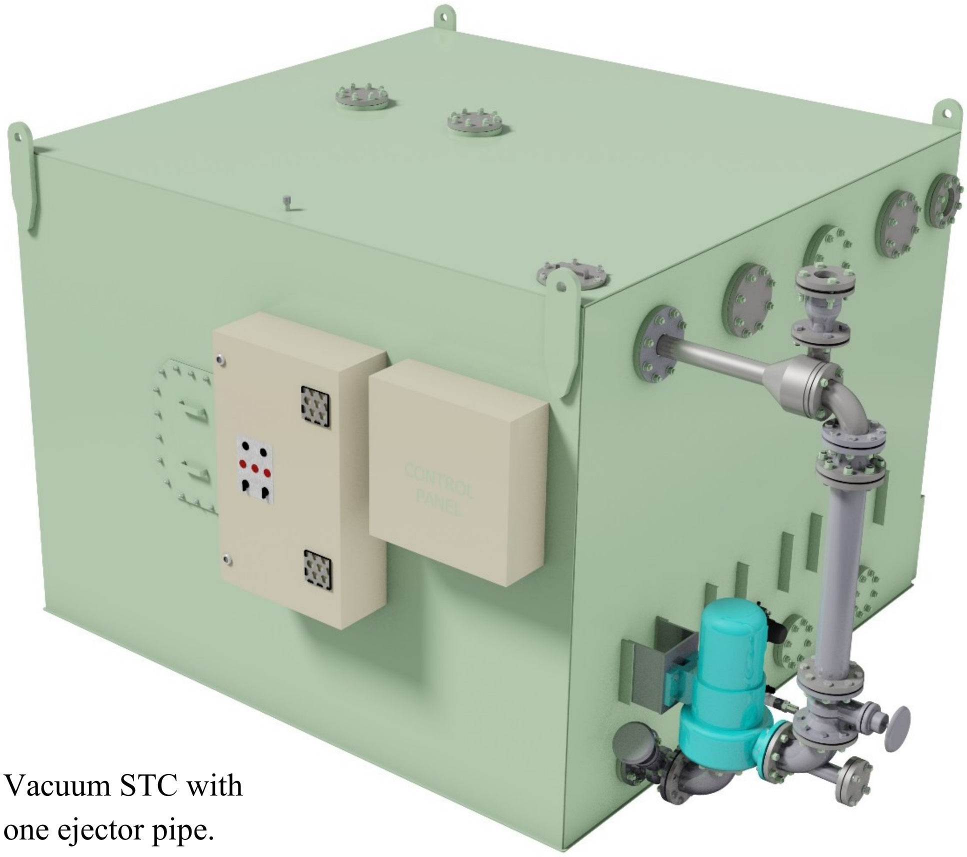


Medium STC.

Large STC.



RTC with three
tanks fitted together.



Vacuum STC with
one ejector pipe.

APPENDIX 4. ASSEMBLY AND PRODUCTION LEAD TIMES OF THE TOP ORDERS BY STC SIZE

Size	Assembly time in workdays	Production lead time of top order in workdays
Small	3	6
Medium	3	6
RTC (medium)	4-5	7-8
Large	6	10

The top order refers to the actual assembly of the STC excluding painting. Painting and drying are an additional 3 days. The production lead time is the time for IQC, FAT and packing added to the assembly time. If the STC has an ejector fitting another 2-3 days are added to the assembly time.

APPENDIX 5. A DETAILED DESCRIPTION OF THE STC ORDER MANAGEMENT PROCESS

Sales orders come from the Poole, the UK or Shanghai, China offices, called “product companies”, sometimes marked “BU”, meaning business unit. By definition (strategic) business units are groupings of a company’s products focusing on product offering to a certain market segment (Jacobs et al. 2011, p. 141). Both Poole and WSZ are in fact part of a business unit, so the term product company is used throughout the thesis.

A naïve forecast is one, where the forecast for a period is equal to the previous period’s actual value (Stevenson 2015, p. 84). WSZ uses the naïve approach with the upcoming year’s forecast adjusted based on the orders confirmed by the product companies. The forecast is used when communicating with the long lead time component suppliers and to a certain extent when thinking about future workforce requirements.

The order processing step starts from the product company asking WSZ whether an order can be shipped on a requested date. At this point WSZ receives information on the type of STC, but no further specifications. The planner calculates backwards from the requested shipping date, at WSZ called the EXW-date, to see whether it can meet it. If the order does not fit the standard lead time, it is called “urgent” and all the steps from Figure 2 are done “as soon as possible”. According to the Incoterms rules (2018) EXW or ex works implies that the seller delivers by placing the goods at an agreed place either on its own premises or another named place. The seller is not responsible for loading the goods on any collecting vehicle or clearing the goods for export (Incoterms rules, 2018). In the case of WSZ delivery is actually FOB or free on board. In this case the seller is responsible for delivering the goods on board a vessel designated by the buyer and the risk of loss or damage of the goods moves onto the buyer once the goods are on board the vessel (Incoterms rules, 2018).

When answering the product company, the planner also calculates backward to establish the freezing point and the PO date. Freezing means that no changes can be made to the order (Jacobs et al. 2011, p. 203). At WSZ purchase orders for the long lead time components are placed after this point, so changes may lead to a longer lead time, which will lead to later delivery. The freezing point is 3 months before the requested delivery date for small STCs and 4 months for other STCs. Planning considers STC06 or smaller to be part of the small STC category and all other STCs, including RTCs, to be part of the “other” category. The PO date is the date that the product company should place the purchase order towards WSZ, including technical documentation, so WSZ engineers can create the PBOM.

After the product company confirms the order and agrees to the dates, the planner should check with the buyer team the availability of long lead time items. For an STC these are the tank and sometimes the blower and pump. The purchasing lead time of a small and medium STC tank is 2 months, for RTC 2-3 months and for a large tank – 4 months. In 2018 the tank supplier informed, that he will not take any new orders after October delivering the last tanks produced by him by the end of the year. A new supplier was searched for and the one found should deliver the first test tank at the end of October. The availability of the blower and pump depends on the type of STC, since different STCs have different blower and pump types. For the most commonly produced STCs there is a small safety stock in China, so delivery time is a week. However, for STC types that have few orders per year, there is no safety stock. The purchasing lead time for the blower is 24 weeks and for the pump 9 weeks, which includes shipping from Europe.

Next WSZ waits for the product company to place the purchase order with all the technical documentation. For STCs the technical documentation means the EBOM or part list made by the product company's engineers. Once the technical documentation is received in-house engineers are given 3 days to change the EBOM into a PBOM and do the routing in SAP. If there is no need to change anything in either BOM, WSZ sends an order acknowledgement to Poole, the order is frozen and the purchase orders for the long lead time components are placed. To change something in the EBOM an ECN or ECR has to be released. An ECN is issued by the product company towards WSZ and an ECR is issued by WSZ towards the product company. An ECN is issued if the customer requests a change or the product company realises it has made a mistake in the EBOM. WSZ releases an ECR if it wishes to change one component that has to be purchased for a similar component that is already available, because it was bought earlier or scrapped from some unsold product.

The structure of a regular STC BOM is shown in the upper part of the figure below and with two ejector fittings in the lower part. The upper example has three top assemblies in the sales order: two actual STCs where the top assembly number ends in -01 and -03, and spares. The sub-assemblies for both STCs are painting, ITA, EA, PA, LDF and wiring. Painting refers to painting the tank. ITA means internal tank assembly and EA external tank assembly. PA refers to assembling the pump to the tank and includes the assembling the pump itself, which is done in-house before starting tank assembly. These three are done by a mechanical worker. LDF refers to liquid dosing fittings and is carried out by the electrical worker. Wiring is also electrical work and includes assembling the blower and control panel to the tank. The control panel is assembled and tested in-house before fitting it on the tank. The sales order shown in the bottom part of the figure below shows additional sub-assemblies related to a vacuum STC like welding ejector pipes and fitting them with the pumps on the tank. This sales order is supplemented with spares, a loose discharge pump and toilets.

Order	Description
004[redacted]	
GO09[redacted]-01	STC40-14 SEWAGE TREATMENT PLANT
9[redacted]-PAINTING	9[redacted]-PAINTING FITTINGS
STC40-ITA-A	STC40 INTERNAL FITTINGS
STC40-EA2-A	2 BLOWER EXTERNAL FITTINGS
STC40-PA2-B	DISCHARGE PUMP FITTINGS
STC-LDF-5	STC01,STC08 TO STC60 DOSING FITTINGS
9[redacted]-WIRING	9[redacted]-WIRING FITTINGS
GO09[redacted]-02	WT418 (SPARES)
GO09[redacted]-03	STC40-14 SEWAGE TREATMENT PLANT

Order	Description
004[redacted]	
GO09[redacted]-01	STC02-13 SEWAGE TREATMENT PLANT (VS)
9[redacted]-PAINTING	PAINTING FITTINGS
STC02-ITA-A	INTERNAL TANK FITTINGS
STC02-EA1-R	STC02 EXTERNAL FITTINGS
STC02-PA1-A	1PUMP FITTINGS 6757100108
STC-LDF-1	STC02-13 DOSING FITTINGS
9[redacted]-WIRING	WIRING FITTINGS
STC02-DWF-J	DILUTION WATER FITTINGS
STC02-E12-J-9[redacted]	1 EJECTOR 2 EJECTOR
9804131023	EJECTOR PANEL 1 EJECTOR 2 PUMPS 220V
STC02-EWB-J	2 EJECTOR PUMPS WIRING
STC02-MFS-J-9[redacted]	FLANGES SINGLE PUMP
GO09[redacted]-02	WT400 (SPARES)
GO09[redacted]-03	STP LOOSE DISCHARGE PUMP
GO09[redacted]-04	AVT13D TOILET

There are three categories of suppliers of STC components. Category A suppliers are located overseas and are chosen and controlled by the product company. Category B suppliers are chosen by the product company but managed by WSZ. Category C suppliers are chosen and controlled by WSZ and are located in Asia, mostly in China. For some basic components VMI is used. When an STC sales order delivery date is agreed upon, it is marked into SAP, which calculates when should purchase orders for the components be placed based on the purchasing lead times marked into SAP. The buyers place purchase orders towards the suppliers when SAP shows that a particular material should be purchased, so they are unaware for which sales order exactly are they purchasing material. One week before the material should be delivered buyers send the supplier a reminder about the order.

If the supplier knows he will be late, he informs the buyers an updated delivery via e-mail. This date should be updated into SAP as the latest confirmation date. It should be noted that you can mark three types of delivery dates into SAP: the statistical delivery date which is the original delivery date requested from the supplier, the latest confirmation date which is eventually the final date the supplier confirms to deliver the material and the actual material arrival date, which the warehouse marks when it receives the material. Currently, supplier on-time delivery performance is determined by comparing the latest confirmation date to the actual material arrival date, which is why suppliers have a nearly 100% OTD performance.

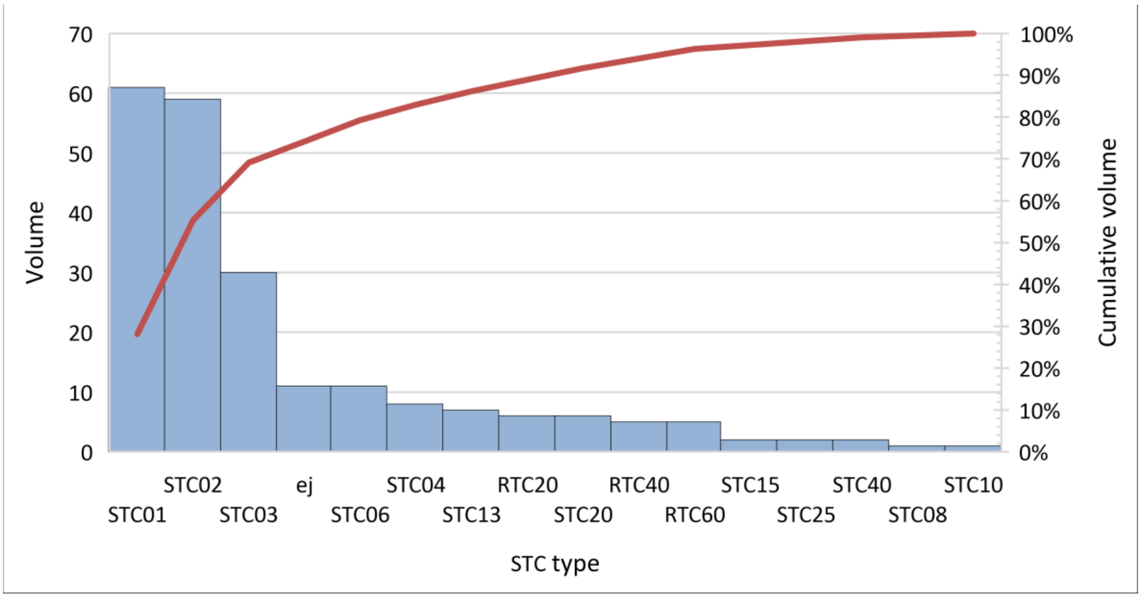
To decrease the disruptions caused by supplier performance local suppliers are requested to deliver material 5 days and overseas suppliers 14 days before the material is needed. Once material arrives to WSZ the warehouse employees mark it into SAP and places it into the warehouse. Some material is quality checked, in which case it is marked with a sticker. If it passes the internal quality control, it is moved into the warehouse racks. Otherwise it is returned to the supplier for rework. Three days are allotted for warehouse and internal control processes.

The planner changes the planned order into a production order based on the date SAP has backward calculated from the delivery date to be the basic start date for an assembly. The planner then informs the warehouse responsible to release the order for picking, so the warehouse employees on the factory floor pick the material needed for a particular order from the racks. There is a daily "planning meeting" which is attended by the planner, buyers, warehouse employees and production supervisors. The planner goes through a spreadsheet where he writes down the orders in WIP which have issues. Sometimes orders whose production is about to start are added to the list if there seem to be issues with. Mostly issues are related to material availability, so the missing material is written down and buyers give the estimated date of arrival of the material. If there is missing material or material shortages in production, the EXW date is pushed forward and the product company is informed of a later delivery. At this point the planner also confirms whether the FAT date requested by the customer can be met.

The basic production process for all STCs is the same: painting and drying the tank, which takes three days, then mechanical and electrical work, internal quality check and then an FAT if it has been requested by the customer, who can choose to be present or just receive the required documentation. For vacuum STCs the ejector pipe welding is done before painting, then the pipe or pipes are sent outside of WSZ for pickling and fitted onto the tank during assembling. If shortages are found during production, the STC is left in the assembly area waiting for the missing material and assembly of a new STC which has material available is started. If the planner feels that the promised FAT and delivery dates will not be met, he informs the product company. Once assembly is finished and the FAT closed, the production order is closed, and the planner sends an invoice to the product company, who sends WSZ shipping instructions. Usually this is when the planner books ship transportation. Logistics operations including packing are outsourced, so the logistics company employees take care of wrapping and delivering the product to the docks for shipment.

APPENDIX 6. DETAILED DATA ANALYSIS FOR PRODUCTS INVOICED DURING THE 19 MONTHS STUDIED

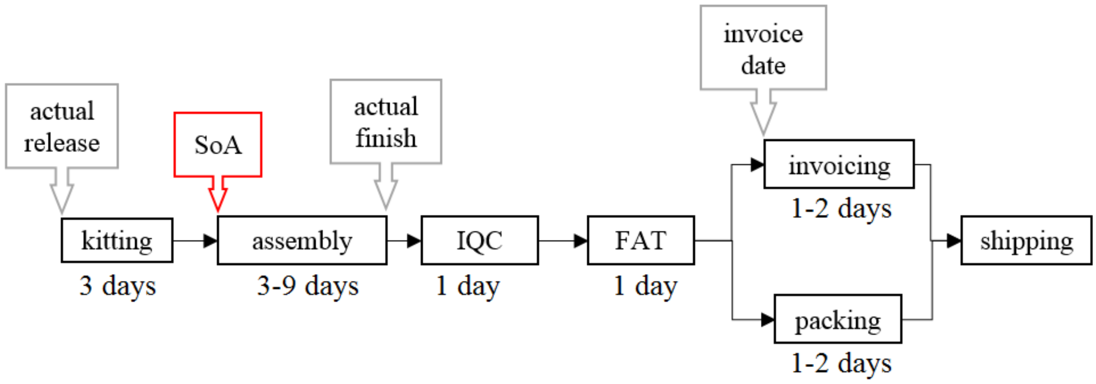
Appendix 6A. Distribution of volumes by type of product



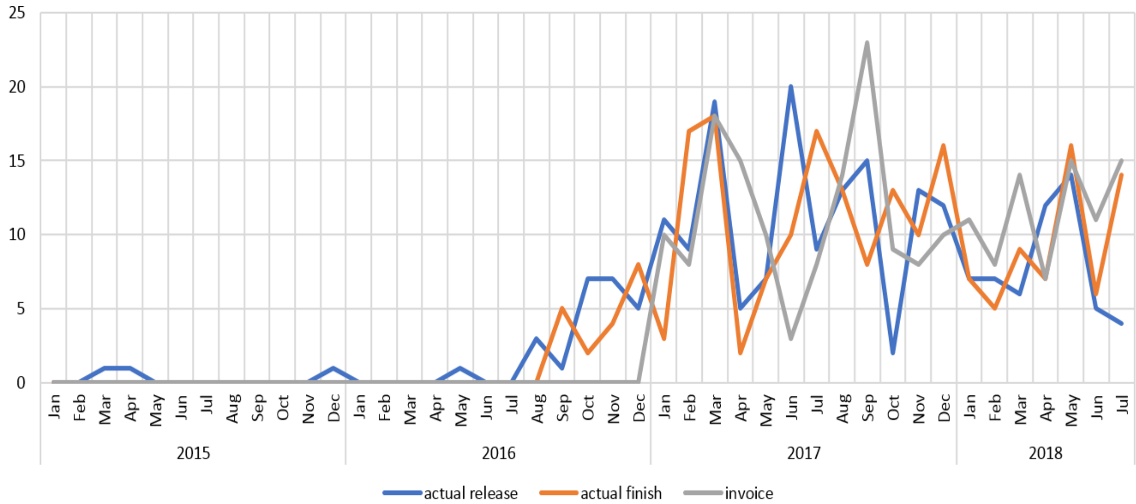
The blue columns show the distribution of invoiced orders by type. The red line shows the cumulative volume of products. Under "ej" are combined all STCs that require ejector fitting. In this case these are seven STC02s, two STC03s, one STC04 and one STC06, so all medium STCs. It can be seen that the most common types are STC01 and STC02 with 80% of the invoiced STCs being small and medium. If the STCs requiring ejector fitting were divided by their type, STC04 would move up and become part of the most common 80%. It is worth noting that the products making up 80% of production do not generate 80% of revenue.

Appendix 6B. Comparing monthly amounts of products released into production, finished and invoiced

Since the top order production lead times range from 8 to 11 days a hypothesis was made that the amount of orders invoiced each month should be roughly the same as the amount of products finished each month and lag behind the amount of products started. The latter based on the fact that production of a product can begin at the end of the month, but the product finished and invoiced only the next month. This would lead us to compare the actual start, actual finish and invoice date. However, in the process of data analysis it was found out, that at WSZ the start date is confirmed to be the same as the finish date, making its comparison to the other dates futile. No other midpoints between the product being released and confirmed finished are marked into SAP. Thus, the dates to be studied were chosen to be the actual release date, that is the day the warehouse is told to kit the order, the actual finish and the invoice date. A rough timeline with the points in question is shown below.

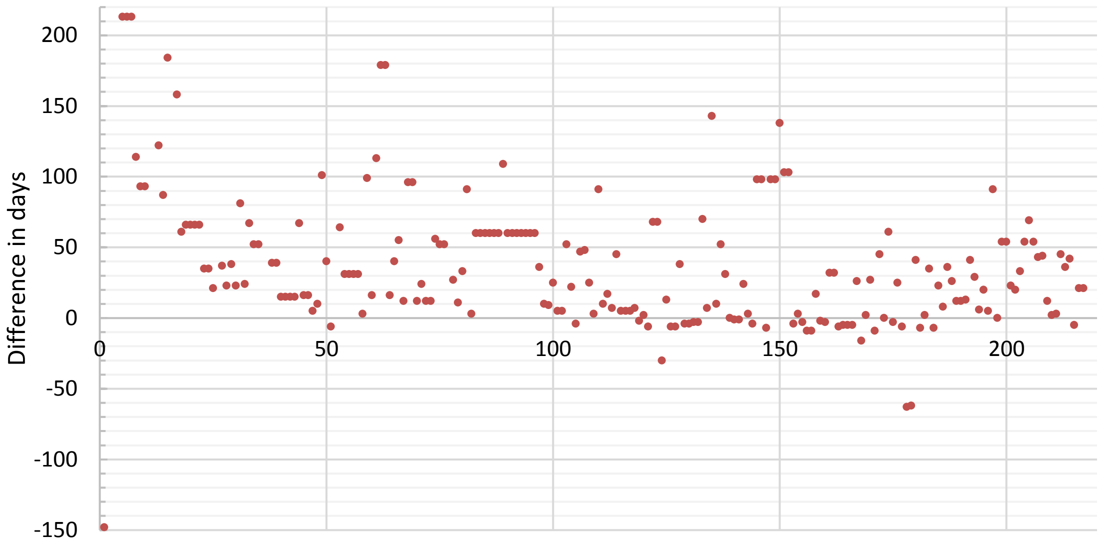


This is why the actual release date is compared to the actual finish and the invoice dates. With all of this in mind a graph showing the amounts of products released to production, finished and invoiced monthly, shown below was constructed, proving the hypothesis wrong.



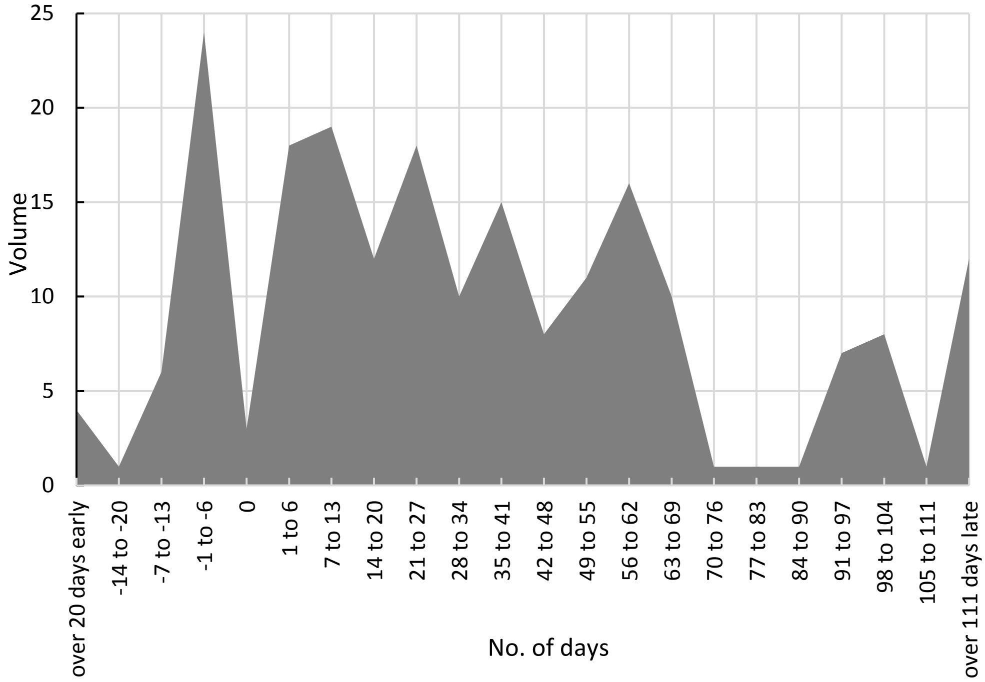
Firstly, it can be seen that in 2015 and the first half of 2016 there are products released into production, but the first products are finished only in the second half of 2016 and the first invoices are placed in January 2017. For the two products whose production was started in 2015 have a production lead time of over 17 months. The STCs in questions are of medium size, so the production lead time should be 8 days.

Appendix 6C. On-time delivery performance



The figure above shows EXW-based on-time delivery performance of STCs invoiced during the 19 months studied. Three different EXW dates are marked into SAP. The first is the date the product company and WSZ agree the ready product to be shipped. It is marked into SAP as the “SAP date”. The second date is the “requested delivery date”, which is the internal deadline for WSZ. In a standard situation there is a difference between the first two, which is equal to the STC size dependent buffer routed into SAP. The third date is what SAP calls the “1st delivery date”, which is the latest date WSZ informs the product company it will deliver. The difference between the last and the “SAP date” is what shows WSZ’s on-time delivery performance. On-time delivery performance for the orders studied is shown in below. As in the earlier data, outliers, in this case if the difference between the two dates is over 250 days, have been deleted. The x-axis is the 0-line showing products that are on time. Products above the line are late and below are early.

It can be that most orders are late. The products are sorted in the order they have been released into production, which means that the further right on the x-axis we go the more recent the orders are. There also seems to be slightly less variability in on-time delivery performance in more recent orders. If we consider this observation and return to Figure 17 it can, however, be noticed that production lead time variability increases in more recent orders. Yet there is not enough proof to tie on-time delivery performance to production lead time variability. What is clear though, that statistically based on SAP data on-time delivery at WSZ is very poor.



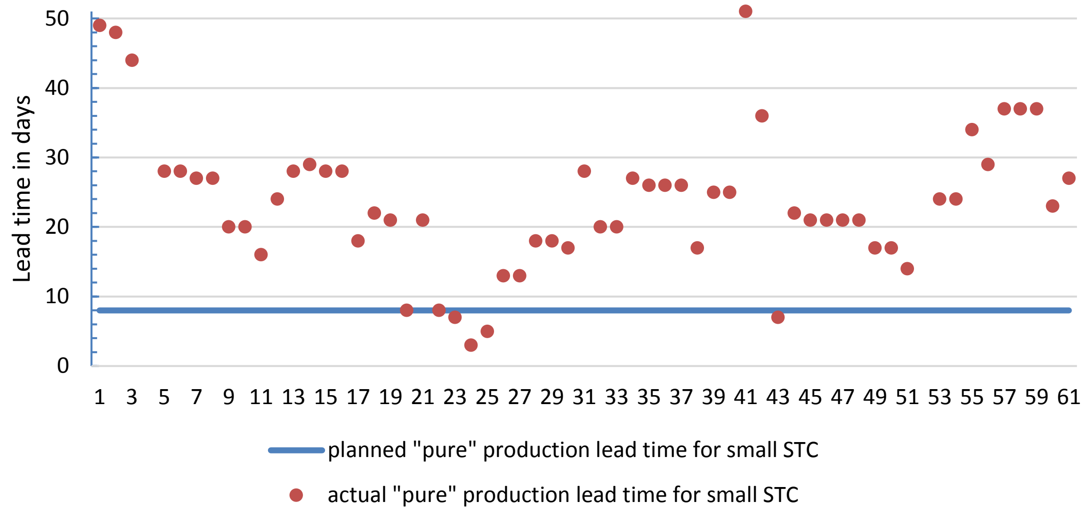
To get a clearer picture of the distribution of product delivery timeliness the figure above was constructed. The horizontal axis shows how much orders are early or late in days. Each segment represents a week. Products that are over 4 months late were grouped together. There is a clear trough at 0, which is the amount of deliveries on time. There is also a peak of deliveries that are early within a one-week time period. Most products are 0-76 days late, with an alarming peak at 2 months. On average a product is 48 days late, so 1,5 months. This again shows how serious the situation at WSZ concerning on-time delivery.

APPENDIX 7. CALCULATION OF THE "PURE" PRODUCTION LEAD TIME

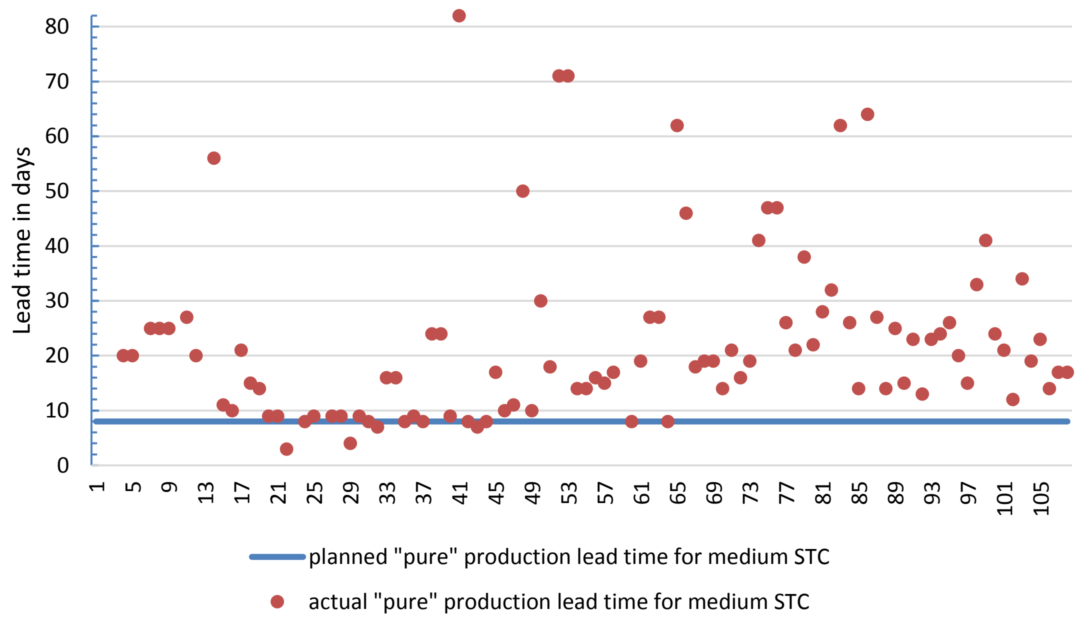
The components of the "pure" production time which includes picking material from the warehouse for the top order, the assembly itself and a weekend balance. The weekend balance is added, so the values can be compared to the data on the actual "pure" production lead times calculated from the data analysed, where some of the production happens on weekends. This makes it possible to talk in days, not workdays.

	small STC	**medium STC**	**RTC**	**large STC**	**medium STC w/ ejector**
picking	3	3	3	3	3
assembly	3	3	5	6	6
weekend balance	2	2	2	2	2
total	**8**	**8**	**10**	**11**	**11**

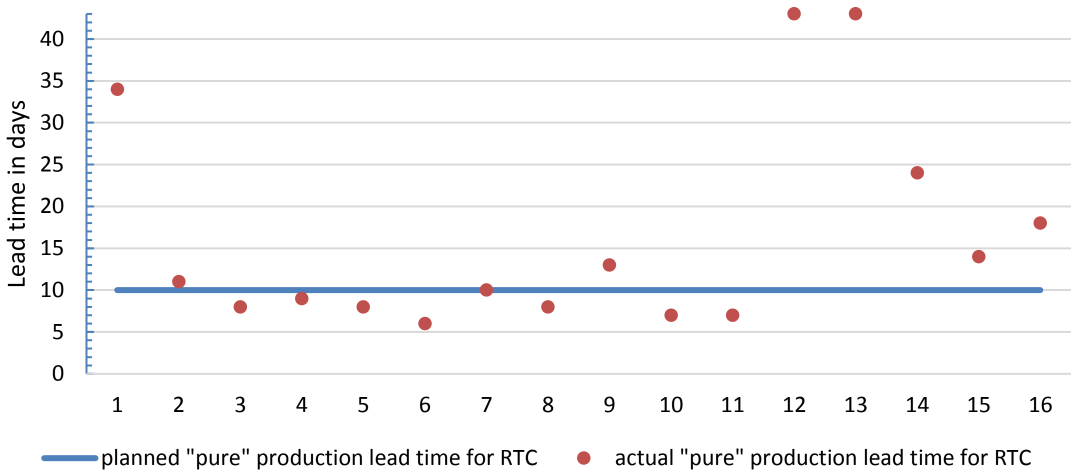
APPENDIX 8. DISTRIBUTION OF "PURE" PRODUCTION LEAD TIMES BY ORDERS WITH REFERENCE TO THE PLANNED LEAD TIME



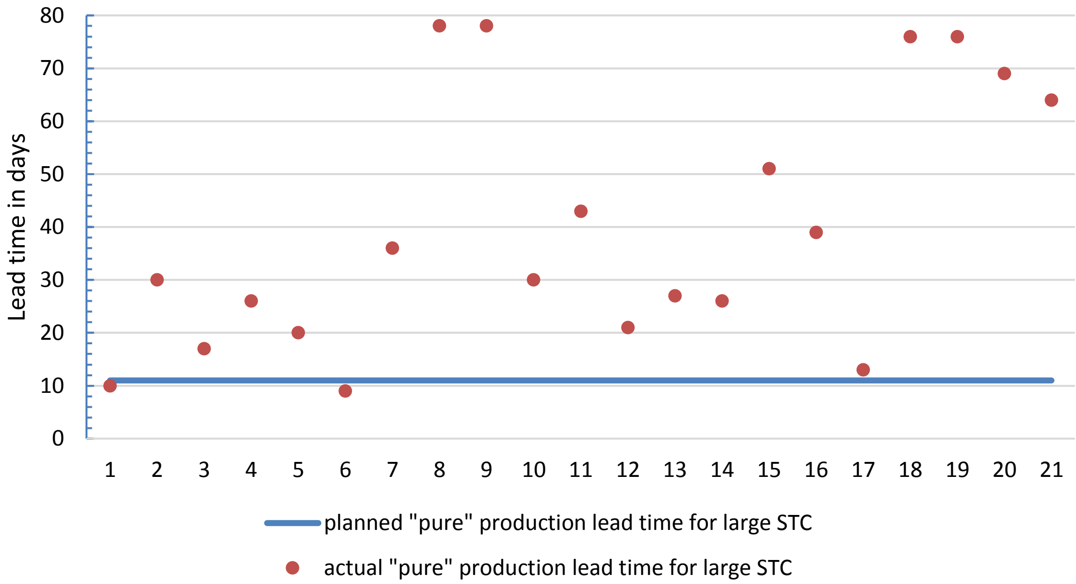
The actual and planned "pure" production lead time for small STCs. The sample size is 61 products with two outliers deleted from the graph. Their lead times were 376 and 112 days.



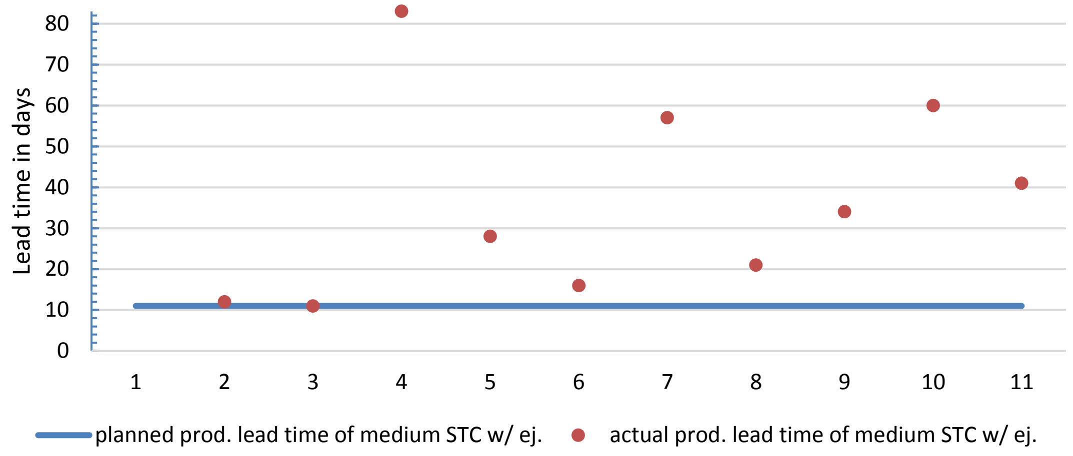
The actual and planned "pure" production lead time for medium STCs. The sample size is 108 products with nine outliers deleted from the graph. Their lead times were 830, 1179, 381, 376, 235, 263, 269, 252 and 205 days.



The actual and planned "pure" production lead time for RTCs. The sample size is 16 products with no outliers.

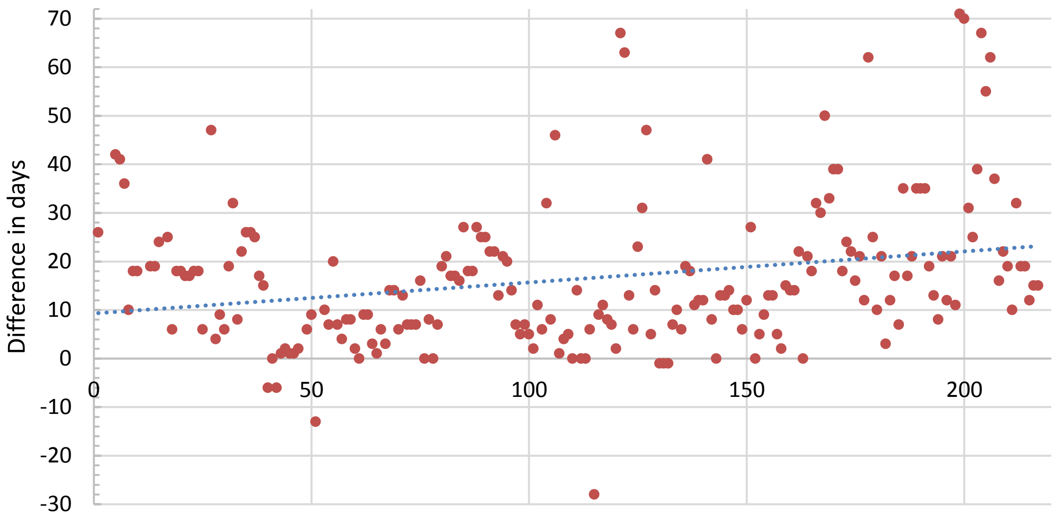


The actual and planned "pure" production lead time for large STCs. The sample size is 21 products with no outliers.



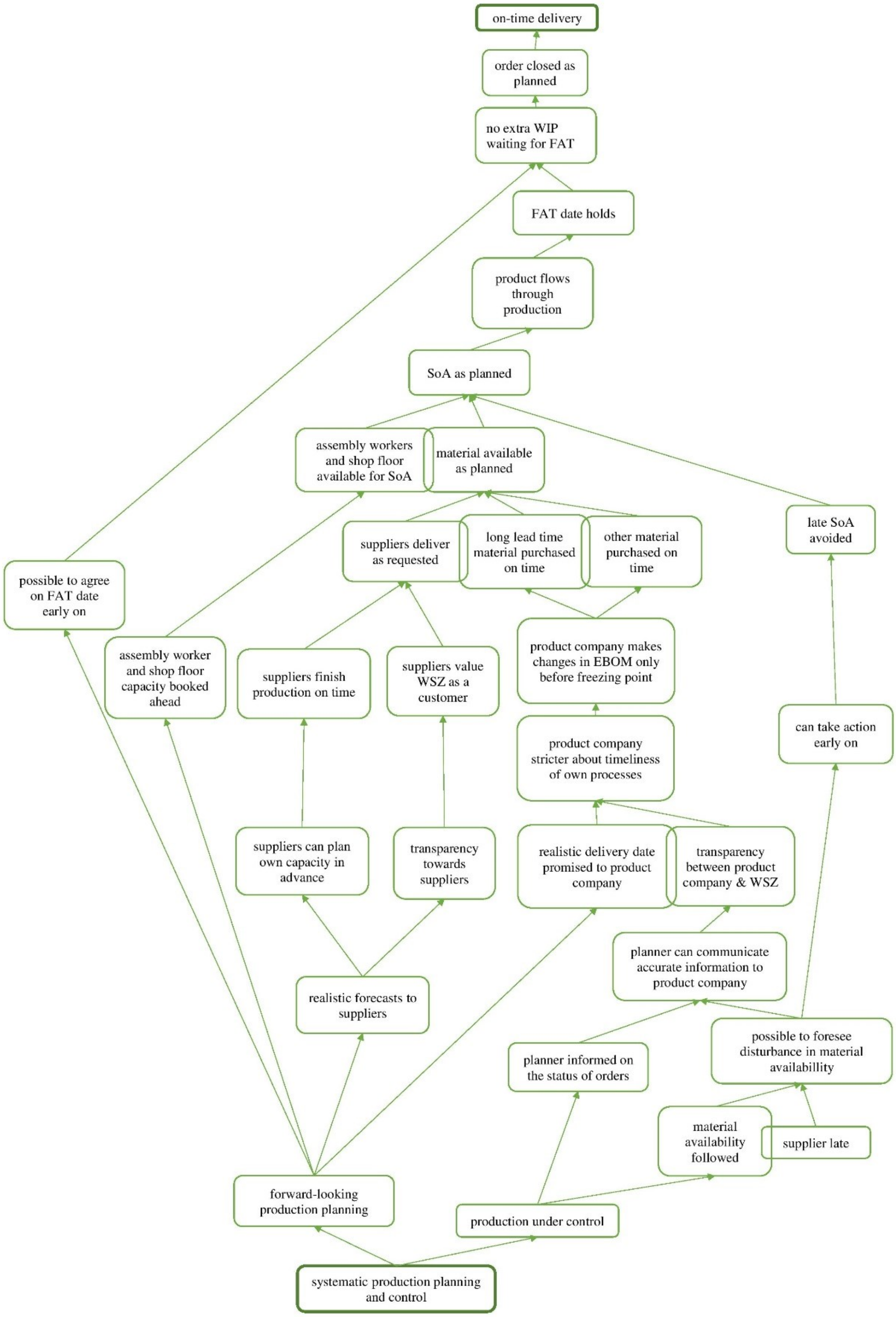
The actual and planned “pure” production lead time for medium STCs with ejector fitting. The sample size is 11 products with one outlier deleted from the graph. Its lead time is 283.

APPENDIX 9. DAY-WISE DISTRIBUTION OF ASSEMBLY FINISHING TIMELINESS

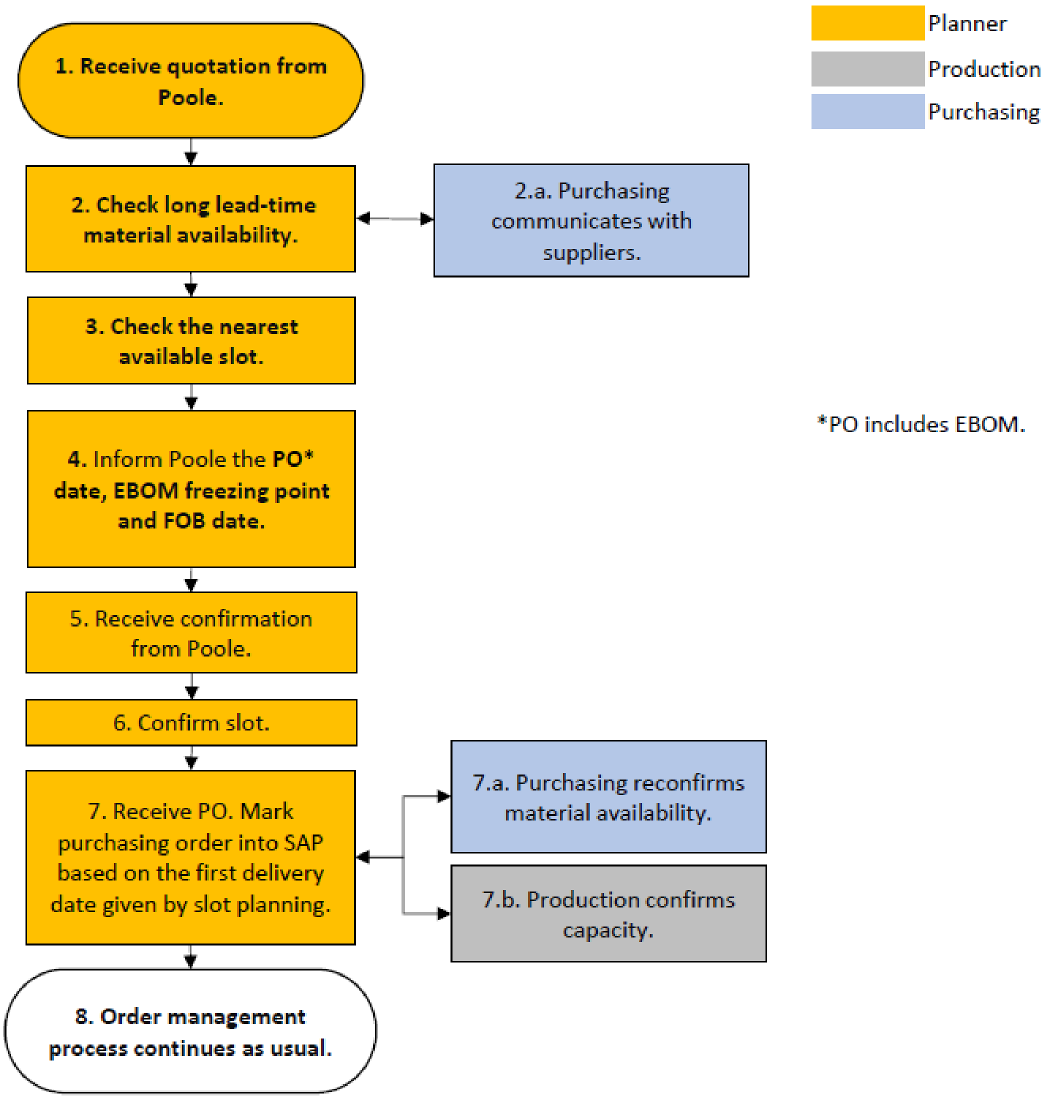


The day-wise distribution of assembly finishing timeliness shows the difference in days between the planned and actual day assembly was finished. The products are in the order they were invoiced, so at the right end of the graph are the most recently finished products. Everything above the x-axis refers to lateness and below to earliness. A trendline has been added to accentuate the worsening performance of assembly finishing timeliness. The sample size is 217 with nine outliers not shown in the figure. Their difference in days was 1173, 272, 380, 368, 368, 231, 257, 261 and 244. The outliers come up in the first 52 products.

APPENDIX 10. FUTURE REALITY TREE



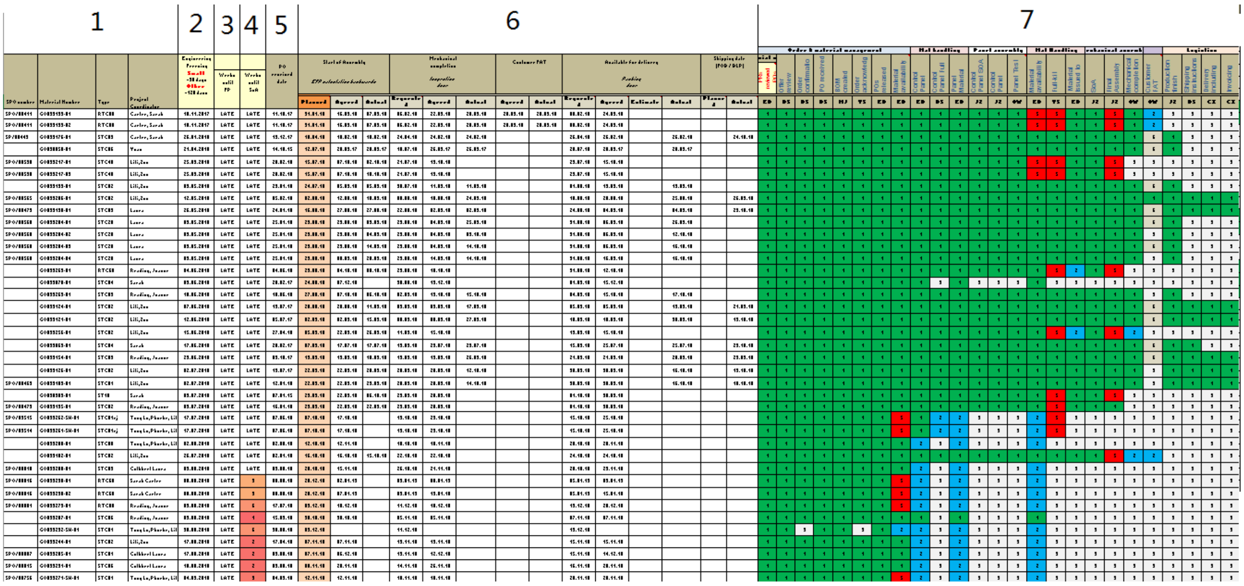
APPENDIX 11. SLOT RESERVATION PROCESS



The slot reservation process starts with the product company, in the case of STC, Poole contacting WSZ with a quotation. The quotation should include information on the type of STC and whether it has some special requirements. Based on their request the product company is given a PO date, a freezing point date and the FOB date. The PO date refers to when Poole should send WSZ the purchase order with the technical documentation. The FOB date is the date the ready product will be on the ship or at the bonded warehouse. This is roughly two weeks after the ready product is available for delivery.

The slot planning spreadsheet is the primary tool used for calculating the schedule. Based on what it gives as the available for delivery date, this is marked into SAP to backward calculate SoA and material purchasing. Slot reservation and confirmation is a two-way deal with the product company. If Poole does not deliver the PO by the given date or makes changes to order after freezing point it loses the slot. If these requirements are met, WSZ promises to hold on to the FOB date. If WSZ does not deliver, it carries the costs.

APPENDIX 12. THE TRAFFIC LIGHTS TOOL

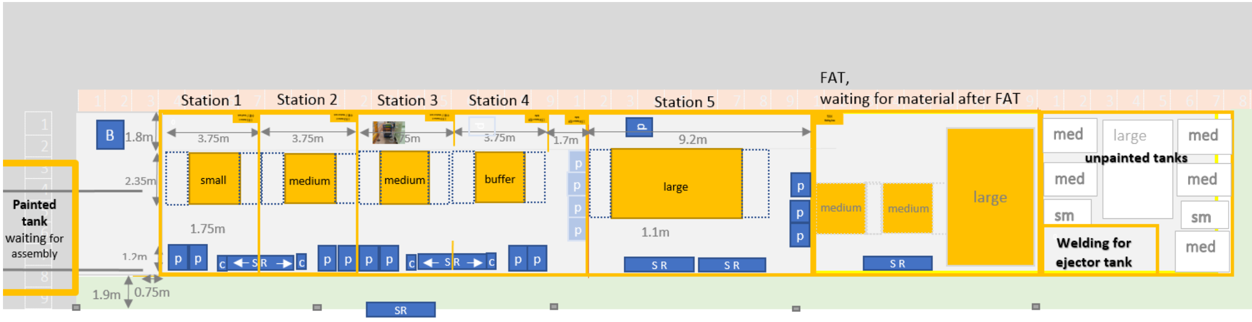


The traffic lights tool is used to track the proceeding of the product by steps. The following information can be found under the numbers marked in the figure above.

1. Basic information on the product: the SAP reference number, the material number used for in-house processes, the type of product and the product company's project coordinator.
2. The freezing point.
3. Number of weeks left until the freezing point.
4. Number of weeks left until SoA.
5. The date the PO from the product company was received.
6. Agreed milestones, updated dates and the actual date the milestone was reached. The milestones are SoA, mechanical completion, customer FAT if required, available for delivery and the shipping date.
7. Production process steps from offer review to invoicing. The status of each step is updated by the person responsible for it. The colours are the following:

1	**Completed**
2	**In process**
3	**Not Started**
4	**Risk**
5	**Issue**
6	**Not applicable**

APPENDIX 13. NEW LAYOUT FOR FULL-KITTING STCS



The new layout for the STC production area consists of 5 stations: one small, two medium, a medium buffer station and one large. Stations 3 and station 4 can be combined into one bigger stations fitting a large STC. To the right of station 5 is the area for STCs that need to pass FAT or received ECNs after FAT and are now waiting for additional material or rework. Further to the right tanks arriving for assembly are placed. This area is also used for welding work on STCs with ejector(s).

The task board is on the left side of the stations, the blue square marked with a “B”. To the left of the station 1 are rails bringing a newly painted tank from the painting room further to the left. The grey area above the stations is the corridor on the other side of which products for another product line, membrane bioreactors, are assembled. Some MBRs are assembled at the supplier’s site, in which case the area can be used as additional buffer for STC production.

APPENDIX 14. THE SHOP FLOOR TASK BOARD FOR STC PRODUCTION

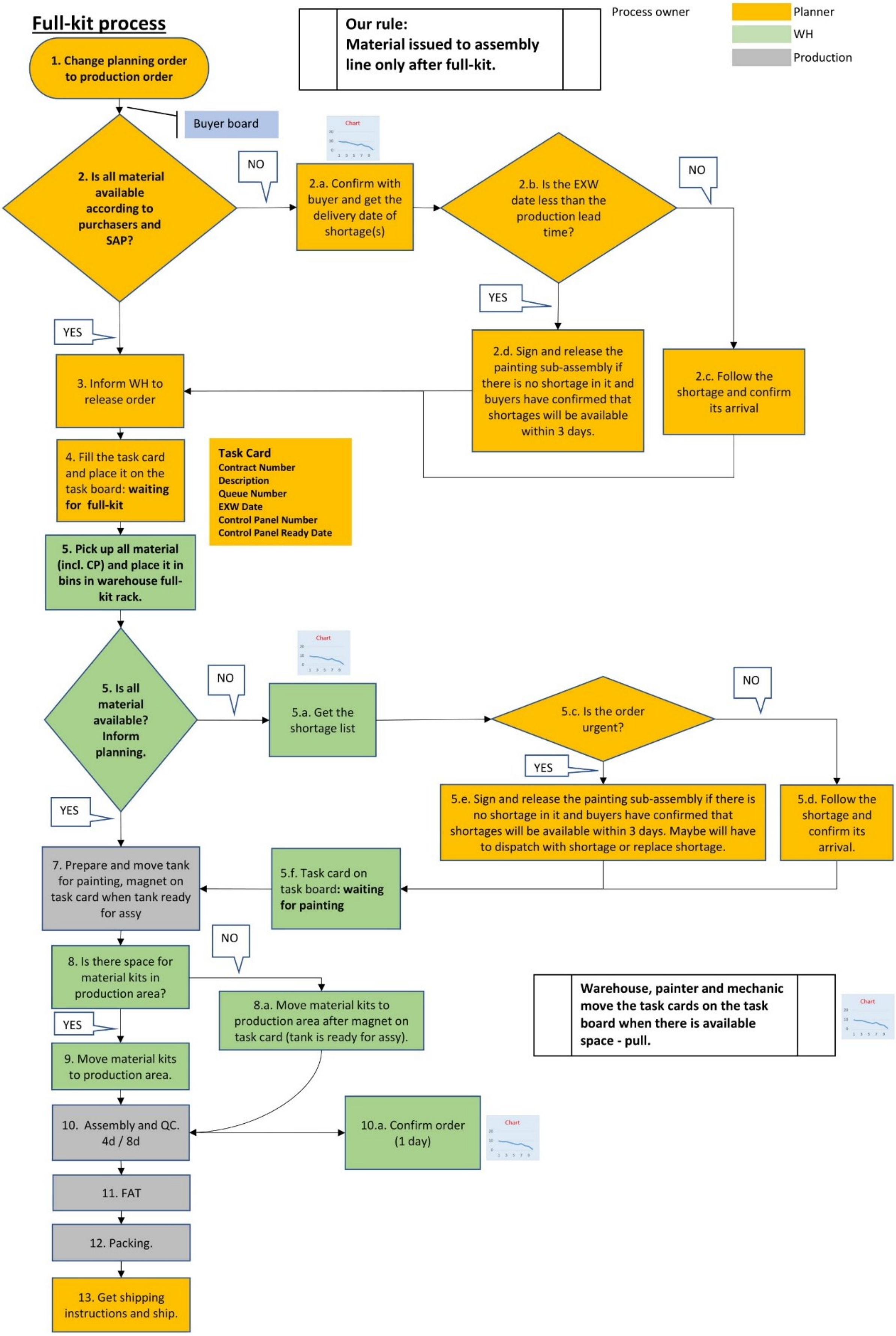
The columns are the layout stations: one for small STCs, two for medium STCs, one buffer for small or medium STCs and one for the large STCs. The buffer station can be combined with the medium STC station to fit a large STC.

The first row shows the products currently being assembled. The second row shows the products being painted or drying. On the last day of drying the painter puts a magnet on the card to show that the material kits can be moved into the assembly area. The third row shows products that have been full-kitted and can now be painted. The fourth row shows the products that need to be kitted next. The bottom row is for products that got ECNs from FAT and are now waiting for the additional material or work needed to close the FAT.

The planner places a task card on the board. There are two sizes of task cards: a smaller for small STC, medium STC and RTC, and a double size for large tanks. This way the card indicates how much floor space the product it represents will take. The planner marks the material number, the type of STC, a queue number, the date the product should be painted i.e. kitting done and whether there will be an FAT and its date. The queue number prioritises the products. A product with a lower queue number should be moved into painting and assembly first.

Once the product is assembled and shipped the card is taken off the board to allow for a next card to move into its place. If the product had an FAT which resulted in an ECN or ECNs requiring waiting for material the card is moved to the bottom of the board and the product moved to a separate waiting area.

APPENDIX 15. FULL-KIT PROCESS CHART

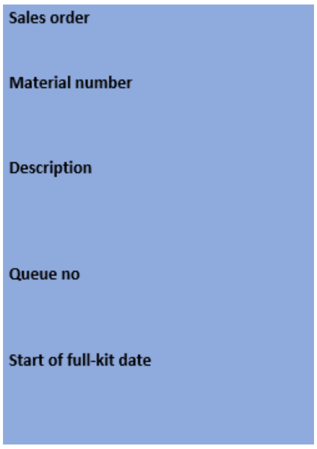


APPENDIX 16. POINTS RAISED IN WEEKLY FULL-KIT MEETINGS

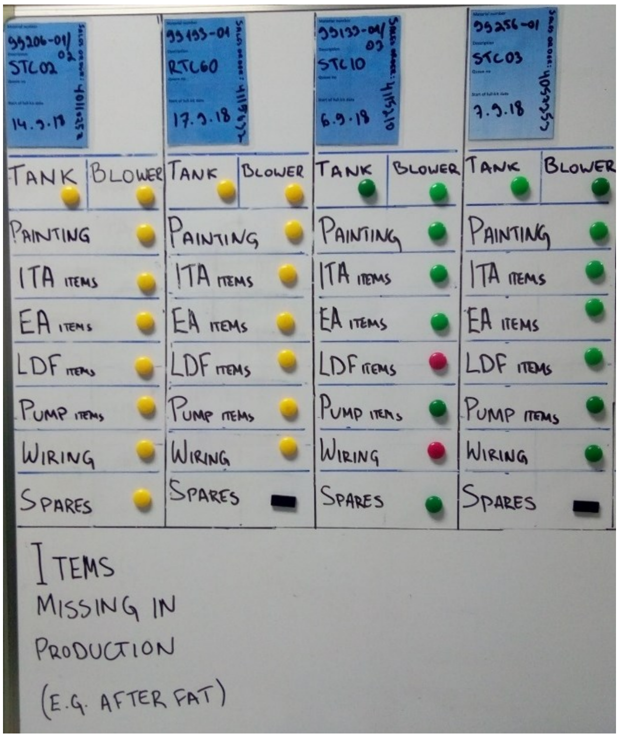
- Adjustments in SAP routings for all sub-assemblies of a top order to be released and start on the same day.
- When changing time-related data in SAP seeing that the changes concern durations not working hours, otherwise finance will have problems with invoicing.
- Changing sales orders from MTS to MTO in SAP resulting in doubled sales orders.
- Rules for what one task card represents. Sometimes one task card represents a whole sales order, sometimes one or two of the top orders inside a sales order. Basic logic, that one card per station, so one tank, which sometimes includes spares or a macerator.
- Clear instruction in Chinese for shop floor employees.

APPENDIX 17. THE BUYER BOARD

One column of the buyer board represents one product. The planner fills in a card with the sales order number, the material number, the type of the product, the queue number and the start of full-kit date. The queue number should be the same here and later on the shop floor task board unless there are some last-minute changes and the customer wants to receive the ready product later. The start of full-kit date is 6 workdays before SoA. The planner then places a card representing the product at the top of the column when he has changed the order from a planned order to a production order.



The buyer then checks that all the material will be available as promise by the suppliers. The column is divided into the sub-assemblies shown in appendix 5 and the buyer marks with magnets the availability of materials for each sub-assembly. The tank and the blower are separated because they are key long lead time.



A green magnet indicates that the materials are physically available and have been kitted. A yellow magnet indicates that the materials are on their way and should be available according to schedule. In an ideal situation all the magnets should be yellow for a product that has just been changed from planned order to production order. A red magnet indicates that there will be issues with the availability of one or more materials of the particular sub-assembly. These are the materials that need to be focused on to see whether the supplier can deliver them as requested or whether they are available for some other order that has a later queue number. The black magnet shows that a sub-assembly is not part of the product.

Once all the magnets are showing full material availability the buyer returns the card to the planner as an indication that production can start. For material that is found missing after SoA a card is placed at the bottom. This can happen if a material quality issue is found during production or after FAT there is need for additional material.

APPENDIX 18. MATERIAL AVAILABILITY MANAGEMENT PROCESS CHART